NA... nference Publication 3236

T... e 1987 G... ddard Space F... ght Center B... ttery Workshop

G. ... w and T. Yi, ***Editors***
NA... ddard Space Flight Center
Gre..., Maryland

Pro... gs of a workshop held at
NA... ddard Space Flight Center
Gre..., Maryland
Nov... 4-5, 1987

Natio... nautics and
Space... istration

Scie... d Technical
Info... Office

199...

PREFACE

This document contains the proceedings of the 20th annual Battery Workshop held at Goddard Space Flight Center, Greenbelt, Maryland on November 4-5, 1987. The Workshop attendees included manufacturers, users, and government representatives interested in the latest developments in battery technology as they relate to high reliability operations and werospace use. The subjects covered included lithium cell technology and safety improvements, nickel-cadmium electrode technology along with associated modifications, flight experience and life testing of nickel-cadmium cells, and nickel-hydrogen applications and technology.

CONTENTS

CONTENTS (Continued)

Page

SESSION III - NiCd

Chairman: Mr. David Baer, Hughes Aircraft

CONTENTS (Continued)

INTRODUCTION

Thomas Y. Yi
Goddard Space Flight Center

On behalf of George Morrow, I would like to thank you for your continuing interest in the annual NASA Battery Workshop. We sincerely hope that the 1987 Workshop was as informative and enlightening as the past Workshops.

As in the past workshops, we have placed emphasis on the existing test programs and recent improvements/events in the aerospace cells and batteries. The first day was devoted to two sessions on general overview of the aerospace batteries and on lithium cell technology. The overview section was opened by an enlightening presentation on "Lessons Learned - Pay Attention" by Mr. Gilbert Roth of NASA/HQ, and concluded with an overview of the NiCd and NiH2 battery program in Japan. The afternoon lithium session covered the cell and battery technology for both the aerospace and terrestrial usage. The second day began with the NiCd session with presentations on both the on-ground life testing and on-orbit data. This was followed by the afternoon session on the NiH2 technology with emphasis on the cell/battery design evaluation and simulated orbital cycling. The Workshop was concluded with a panel discussion on the merits of the KOH concentration on the NiCd and NiH2 cells. The panel discussion was moderated by Dr. Lawrence Thaller of NASA Lewis Research Center, with opening remarks by Dr. Hong Lim of Hughes Aircraft and Mr. James Dunlop of COMSAT Labs.

We would like to thank all the people that helped making the 1987 Workshop a success. We would like to thank the attendees, presenters, and especially the session chairmen for the time and effort they have put in, for making the Workshop an active forum for discussion of aerospace cells and batteries.

SESSION I

FLIGHT OVERVIEWS

Chairman: Mr. Thomas Y. Yi, GSFC

"LESSONS LEARNED-PAY ATTENTION"

GILBERT ROTH

The first speaker was Gilbert Roth from NASA Headquarters on "Lessons Learned-Pay Attention!" Roth heads the Aerospace Advisory Panel (ASAP) established by Congress in 1967 and in continuous existence since then. There are nine members in the Panel--none from NASA other than Roth--and five consultants.

Roth pointed out that we must use our experience base--we never seem to learn from what should have been lessons learned. He called attention to the "under 40, over 40" syndrome: Those under the age of 40 find it difficult to imagine that those over 40 have been through what they are going through, and conversely those over 40 find it difficult to imagine that others may not know of their successes and failures. Lessons learned do appear as standards in company documents. Roth cautioned against excessive use of acronyms because they can lead to loss of intelligibility. In briefings, the audience may not wish to admit its ignorance of insider acronyms and therefore miss the point that is being made. (See viewgraph in the form of a letter from the office of the NASA Administrator, Roth [Figure 4].)

Roth cautioned against excessive reliance on review procedures to catch errors before they become disasters.

Regarding safety issues, Roth said that ignoring "small problems" can ultimately lead to big problems. There is a tendency to try to solve extremely unlikely but potentially catastrophic problems, and to ignore the more likely problems that do not appear to be catastrophic.

Roth presented a viewgraph based on a letter from E. Schmerling, which described the possibility of an explosion due to Lithium batteries in AT-type computers, (Roth [Figure 10]).

The Power Information Center issues summaries of the status of R & D for electrochemical systems (Roth [Figure 11]).

LESSONS LEARNED

GIL ROTH
AEROSPACE SAFETY ADVISORY PANEL - NASA HQ

1987 NASA/GSFC BATTERY WORKSHOP - NOVEMBER 4, 1987

FIGURE 1. ROTH

LESSONS LEARNED...........

FIRST AND FOREMOST KEEP IN MIND:

- o THE ONLY LESSON WE SEEM TO LEARN IS THAT WE NEVER LEARN FROM LESSONS LEARNED!
- o IF YOUR UNDER 40 IT IS DIFFICULT TO IMAGINE THAT THOSE OVER 40 HAVE BEEN THROUGH WHAT "YOU" ARE GOING THROUGH AND THOSE OVER 40 FIND IT DIFFICULT TO IMAGINE THAT OTHERS MAY NOT KNOW OF THEIR SUCCESSES AND FAILURES!
- o LESSONS LEARNED ARE IN EFFECT THE HISTORY, THE EVOLUTION OF TECHNOLOGICAL AND SCIENTIFIC ADVANCEMENT.

FIGURE 2. ROTH

SOME THOUGHTS ON LESSONS LEARNED

1. THERE IS MORE THAN A SMALL GRAIN OF TRUTH IN THE OLD ADAGE THAT A TIME COMES IN THE LIFE OF EVERY PROJECT WHEN YOU HAVE TO SHOOT THE ENGINEERS IN ORDER TO GET ON WITH THE JOB.
   A. STOP THEORIZING AND DO PRACTICAL APPLICATIONS
   B. BUILD WHAT HAS BEEN DESIGNED
   C. STOP THE CHANGES
2. AT THE SAME TIME WE MIGHT "TAKE CARE" OF THE ACRONYM AND ABBREVIATION MANIACS....SEE THE NASA HQS MEMO.
3. THERE IS DANGER IN PLACING UNDUE RELIANCE UPON AN ELABORATE STRUCTURE OF REVIEW AND OVERSIGHT GROUPS IN THAT IT CAN BECOME A JUSTIFICATION FOR NOT DOING THE JOB CORRECTLY IN THE FIRST PLACE. "NOT TO WORRY," SAYS THE MANAGER TO HIMSELF, "THE RELIABILITY AND QUALITY ASSURANCE GUYS DOWN THE LINE WILL CATCH ANY PROBLEMS."
4. TEMPTATIONS TOWARD EXAGGERATING THE BENEFITS AND UNDERSTATING THE COSTS OF A PROJECT ARE GREAT. THIS OFTEN RESULTS IN A TANGLED WEB WHICH NEVER GETS BETTER, OFTEN GETS MUCH WORSE.

FIGURE 3. ROTH

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

September 1, 1987

TO: Officials-in-Charge of Headquarters Offices

FROM: AE/Exeutive Officer

SUBJECT: Acronymous

"At a recent GMSR, the OSTS and the OSS discussed with A, AD, and AD-P the ALS, ASRM, SDV, and ELV aspects of the Shuttle and the Station. A part of this discussion was the need for an FRR to be conducted prior to the FRF but after the CDDT for STS-26 or STS-71-A, and that the FRR be held at JSC, NSTL, or KSC. J.R. thought it should be conducted at MSFC at the same time as the OMSF-MC meeting. Having or not having an FRF for STS-26 might not be important to CRAF, AXAF, or even HRSO, but it is nevertheless tru that OSTS could use more OA for the test and hence more BA than first envisioned."

The above paragraph is a fake; it is unreal, inaccurate, and unintelligible to most people who read it. However, it is representative of where our internal use of acronyms are jargon is taking the reader. In short, our communications are becoming uncommunicative to most people.

It is requested that both internal as well as external written and oral communications explain the acronym or the vernacular terms the first time they are used in the written correspondence or in a briefing.

Otherwise, we may never reach the people who could add a suggestion, agree with the precept, or praise our good, intelligent, and original work simply because they cannot understand us.

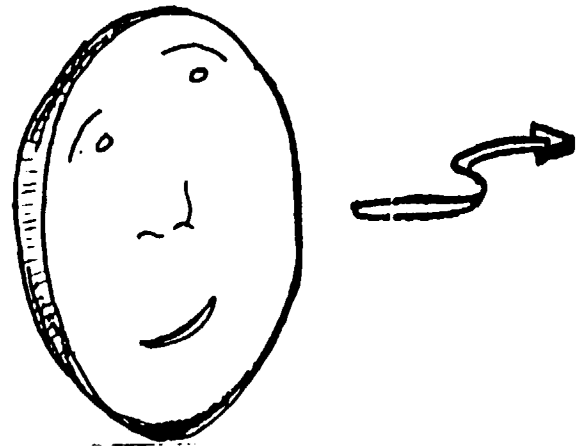
Henry E. Clements

Henry E. Clements
Executive Officer

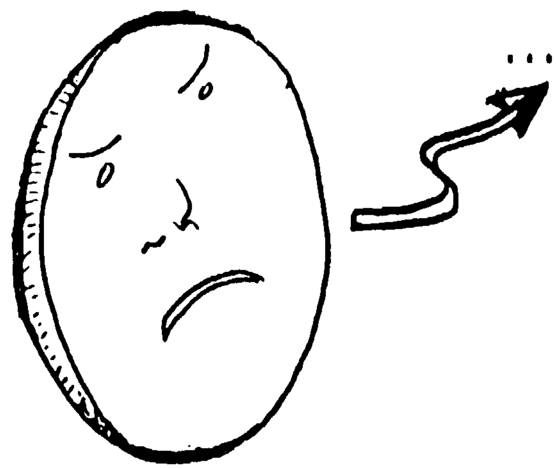
5. ONE GETS A DEPRESSING SENSE OF DEJA VU AS YOU READ THE FINDINGS OF INVESTIGATING BOARDS (E.G., THE MARCH 26, 1987 ATLAS-CENTAUR FAILURE, THE STS-25 CHALLENGER ACCIDENT, AND SO ON). TIME WAS NOT REALLY OF THE ESSENCE AND EVERYONE WOULD VERY WELL HAVE BEEN PAINSTAKINGLY CAREFUL. MAKING ROBOT-LIKE REVIEWS OF TECHNICAL DATA ON ISSUES SUCH AS WEATHER CONDITIONS AND CONSTRAINTS MUST NOT BE DONE....WITHIN REASON ERR ON THE SIDE OF CAUTION AND COMMON SENSE.
6. SOME THOUGHTS WITH REGARD TO "SAFETY"

FIGURE 5. ROTH

- JUST AS EVERY COIN HAS TWO SIDES...SO DOES SAFETY...PARTICULARLY AEROSPACE SAFETY.

- 

  THE MAJOR PROBLEMS ALWAYS RECEIVE EVERYONE"S RAPT ATTENTION........

- 

  .....MEANWHILE....THE LITTLE THINGS, THE SO-CALLED "SMALL PROBLEMS" ARE OFTEN NEGLECTED, SENT TO THE BOTTOM OF THE WORK PILE

- FOR A MOMENT LET US FOCUS IN ON THOSE LITTLE THINGS THAT END UP MEANING A LOT!!!

FIGURE 6. ROTH

FIRST....WHY WORRY?

0 HISTORY TELLS US THAT ALTHOUGH SMALL PROBLEMS ARE RESOLVED AS TIME AND MONEY PERMIT, THOSE THAT ARE NOT RESOLVED OFTEN LEAD TO SUBSTANTIAL HARDWARE, DOLLAR AND SCHEDULE LOSSES.

A SYNDROME WE MIGHT CALL: "THE HIGH COST OF ATTENDING TO NITS"

(NIT = PARASITIC INSECT EGG = LITTLE PROBLEMS)

0

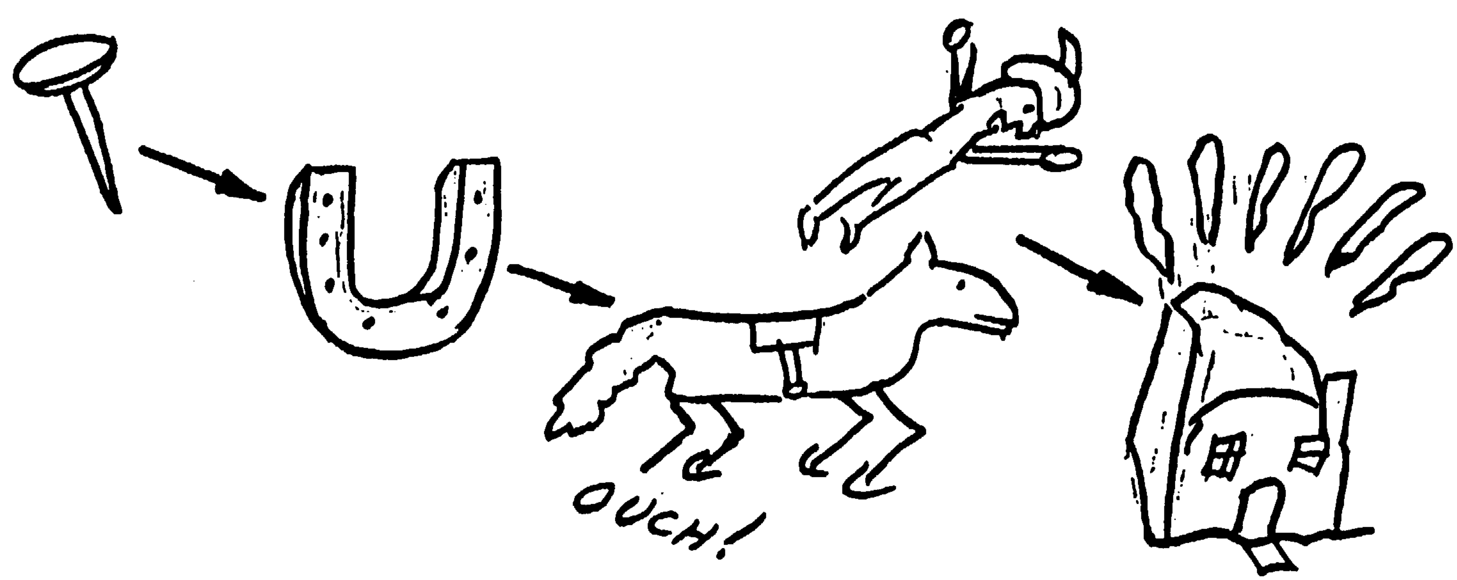


FIGURE 7. ROTH

7. TECHNICAL COMMUNICATIONS....FAILURE TO COMMUNICATE

LET'S GO BACK IN HISTORY,

> "....THE FAILURE TO COMMUNICATE...MAY WELL STAND AS ONE OF THE BASIC CAUSES OF THE PEARL HARBOR TRAGEDY, SECOND ONLY TO THE FAILURE TO BELIEVE IN ITS POSSIBILITY. ONE BY ONE THESE FAILURES PASS IN SORRY REVIEW: FAILURE TO ENSURE UNDERSTANDING; FAILURE OF SENIORS TO SUPPLY ALL AVAILABLE RELEVANT INFORMATION TO JUNIORS; FAILURE TO SUPERVISE AND FOLLOW THROUGH; FAILURE OF JUNIORS TO BE SURE THEY UNDERSTOOD THEIR SENIORS; LACK OF CLARITY OF EXPRESSION." ("PEARL HARBOR: THE VERDICT OF HISTORY")

8. AS A DESIGNER, TEST ENGINEER, MANUFACTURING ENGINEER AND PROCESS CONTROLLER, TECHNICAL MANAGER YOU HAVE THE RESPONSIBILITY TO RECOGNIZE RISKS, ASSESS THEM, COMMUNICATE JUDGEMENTS, ACCEPT OR CORRECT THEM.

FIGURE 8. ROTH

FIGURE 9. ROTH

Posted: Fri Apr 10, 1987 9:12 PM EST
From: ESCHMERLING
To: hq
Subj: Caution on computer batteries

Msg: JGIH-2551-4701

I have no personal experience of Lithium battery explosions, but have now heard warnings from several, usually reliable, sources. I therefore pass on the following, courtesy of a local computer bulletin board:

YOU MAY HAVE A TIMEBOMB IN YOUR COMPUTER....

If you have an AT type machine, it may literally contain a timebomb! The warning comes from Alex Papakyriakou, General Manager, of International Battery Corporation, Reseda, CA, and exclusive marketer of Tadiran lithium replacement batteries. (Tadiran supplies about 80% of the AT's, compatibles, and clones.) I, a battery engineer, am also adding to this warning

High rate lithium batteries may explode when they reach a very low level of charge due to internal gas pressure buildup. This can be created by shorts within the cells occurring from dendritic calcium growths that can take place when the battery nears the end of life External short circuits can cause explosions as well. The problem is potentially inherent in high rate lithium batteries because of their particular chemical system. The problem does NOT affect low rate systems such as found in watches

When the battery is discharged--in anywhere from a few months to a few years, depending on quality--the clock will begin flashing the incorrect time, and you will receive configuration error messages on bootup It is important that you dispose of the battery immediately! It is also important that you replace the unit with one that is UL approved and has undergone rigorous aging, short circuit, crush and heat testing Better batteries will often include an internal resistor to limit current flow

Batteries which are not UL approved tend to be supplied with lower cost clones. It is worth taking you machine apart to look for the UL logo, a reverse "R" joined to a "U." IBC's Tadiran batteries are guaranteed for 3 years in use and a shelf life of 10 years. For info, call Sonja Hurty at IBC, (818) 609-0516 (6860 Canby Ave, Suite 113, Reseda, CA, 91335)

Mel Morganstein

FIGURE 10. ROTH

INTERAGENCY ADVANCED POWER GROUP

POWER INFORMATION CENTER BRIEF

PIC Number 3942
Working Group CHEMICAL
Field of Interest C-EC
Revision Number 1
Revision Date July 1987

CHEMICAL PROJECT BRIEFS describe the status of all R&D programs submitted to the Power Information Center by the government sponsors in electrochemical systems, including chemical batteries, biochemical devices, simple fuel cell systems, chemical regenerative fuel cell systems, and chemical and thermal energy storage. This document is not to be reproduced, in whole or in part, for dissemination outside your own organization nor may it be reproduced, in whole or in part, for advertising or sales promotion purposes.

Project Title: Sodium-Sulfur Space Cell Development	
Initial Date 5/00/86	Probable Completion Date: 12/00/87
Directing Agency: AFWAL/W-P .	Agency ID # 31452209
Contracting Organization: Ford Aerospace & Communications Corp. 3939 Fabian Way Palo Alto, CA 94303-9981	Contract # F33615-85-C-2540
Principal Investigator: Don Briggs Telephone Number: 415-852-5055	
Project Manager: Douglas M. Allen AFWAL/POOS-2 Wright-Patterson AFB, OH 45433 Telephone Number: 513-255-7770	
Index Terms: Carbon Cathodes, Beta" Alumina/ZrO_2, Seals	
Related PIC Projects:	

POWER INFORMATION CENTER
CSR, Incorporated • 1400 Eye Street, N.W., Suite 600
Washington, D.C. 20005 • 202-842-7600

FIGURE 11. ROTH

"JPL FLIGHT PROGRAM REVIEWS"

KARLA CLARK

Karla Clark (JPL), gave the presentation "JPL Flight Program Reviews." Five flight programs were described along with a NiCd RTOP program.

The Magellan mission will map 90 percent of the Venusian surface during which the batteries will be subjected to 18003.1hour day/night cycles. There will be a 1.5 year cruise to Venus. The battery design consists of 2/26.5AH batteries with a 28V unregulated bus. There are 22 cells per battery. The batteries will face highly variable Venusian orbit cycles, for the DOD varies from 7 to 35 percent.

The Galileo Orbiter is a planetary mission to Jupiter baselined for the 1991 launch. The battery which will be subjected to a 6 year cruise are planned to be used only twice. It will supplement the RTG as well as provide load leveling capability. It will consist of 18 15AH cells.

The Galileo Probe will have 3 $LiSO_2$ battery modules which will provide 19.4AH capacity. The probe will be released 150 days prior to arrival at Jupiter. The batteries will provide 6.25 hours of pre-entry power as well as 48 minutes of discharge during descent.

TOPEX is scheduled for a 3-year LEO orbit which may be extended to 5 years. It will have a 102 minute orbit (77 min charge/35 minute discharge). It will use 3 50AH NASA Standard Batteries of the MPS design built by McDonnel Douglas. The batteries will be subjected to a nominal DOD of 12 percent.

Although the Mars Observer is baselined for a 1990 launch, the actual date has slipped to FY92. It will use 2/26.5AH batteries of the DMSP/TIROS design. There will be a 1 year cruise, followed by 700 earth days of orbital mapping Mars. This is equivalent of a total 8400 day/night cycles (79/39 minute day/night). The batteries will have a DOD of 24 to 27 percent. There is independent charge control of the 2 batteries. The batteries will be charged with constant potential with a set C/D, then trickle.

Mariner Mark II (CRAF) is in the pre-project phase and will be built in-house at JPL. It will fly in formation for 4 years with the comet Temple II, and during the time, it will send a penetrator down to the comet surface. A three year cruise is anticipated, followed by a 4 year mission. The battery design consists of 32 cells with 30V regulated bus. There will be a partial reconditioning capability.

The last topic is the NiCd RTOP in which JPL intends to understand the NiCd technology by developing a prediction model and an accelerated test regime. A number of items such as electrochemical principles, manufacturing data, and performance data will be compared to generate the prediction model.

JPL

JPL FLIGHT PROGRAM OVERVIEW

1987 NASA/GSFC BATTERY WORKSHOP

BY

KARLA B. CLARK
PAUL TIMMERMAN

JET PROPULSION LABORATORY
NOVEMBER 4, 1987

FIGURE 1. K. CLARK

JPL

SUMMARY

PROGRAM	PRIME	LAUNCH
MAGELLAN	MMC	1989
GALILEO	JPL	1989/91
TOPEX	FAIRCHILD	1991
MARS OBSERVER	RCA	1990/92
MARINER MARK II (CRAF)	JPL	1993 (?)
Ni-Cd RTOP	JPL	----

FIGURE 2. K. CLARK

JPL

MAGELLAN
(VENUS)

MISSION DESIGN

- 1.5 YEAR CRUISE
- 3.1 HOUR ORBIT
- 1800 (EXTENDED MISSION LIKELY) CYCLES
- HIGHLY VARIABLE DAY/NIGHT CYCLES

BATTERY SYSTEM DESIGN

- 28 V UNREGULATED BUS
- 2 26.5 AH BATTERIES
- 22 CELLS PER BATTERY
- VARIABLE DOD, 7 - 35%
- CONSTANT POTENTIAL CHARGING (PARALLEL)
- PARTIAL RECONDITIONING CAPABILITY

FIGURE 3. K. CLARK

JPL

MARS OBSERVER
(BASELINE 1990 LAUNCH)

MISSION DESIGN

- 1 YEAR CRUISE
- 700 EARTH DAYS OF ORBITAL MAPPING
    - TOTAL 8400 DAY/NIGHT CYCLES
    - 79/39 MINUTE DAY/NIGHT

BATTERY SYSTEM
DESIGN

- 28 V REGULATED BUS
- 2 26.5 AH BATTERIES (DMSP/TIROS DESIGN)
- DOD MAINTAINED AT 24-27% DOD
- CONSTANT POTENTIAL CHARGING WITH C/D LIMIT SWITCH TO TRICKLE CHARGE
- INDEPENDENT CHARGE CONTROL
- 7.5 A MAXIMUM CURRENT TO BATTERIES
- RECONDITIONING CIRCUIT AVAILABLE

JPL

GALILEO ORBITER
(JUPITER)
(BASELINE 1991 LAUNCH)

MISSION DESIGN

- 6 YEARS CRUISE
- NO FIXED ORBITAL TIME
    - NO FIXED BATTERY DISCHARGE TIMES
- RTG BASELINE

BATTERY SYSTEM
DESIGN

- ONLY FOR 1991 LAUNCH
- LOAD LEVELING CAPABILITY
- 30 V REGULATED BUS
- 1 15 AH BATTERY
- 18 CELLS PER BATTERY
- CONSTANT POTENTIAL CHARGING
- RECONDITIONING CAPABILITY UNDECIDED

FIGURE 5. K. CLARK

JPL

GALILEO PROBE
(JUPITER)

MISSION DESIGN

- AMES RESEARCH CENTER RESPONSIBILITY
- RELEASE 150 DAYS PRIOR TO ARRIVAL AT JUPITER
- 6.25 HOURS OF PRE-ENTRY POWER
- 48 MINUTES DISCHARGE DURING DESCENT

BATTERY SYSTEM DESIGN

- 3 $LiSO_2$ MODULES
- 19.4 AH TOTAL REQUIRED

FIGURE 6. K. CLARK

JPL

TOPEX
(EARTH)

MISSION DESIGN

- 3 YEARS LOW EARTH ORBIT (EXTENDABLE TO 5 YEARS)
  - 77/35 MINUTE DAY/NIGHT

BATTERY SYSTEM DESIGN

- MPS DESIGN (McDONNEL DOUGLAS)
- UNREGULATED BUS
- 3 50 AH NASA STANDARD BATTERIES
- 22 CELLS PER BATTERY
- NOMINAL DOD 12%
- CONSTANT POTENTIAL CHARGING (PARALLEL)
- PEAK POWER POINT TRACKING SOLAR ARRAY

FIGURE 7. K. CLARK

JPL

MARINER MARK II
(CRAF)

MISSION DESIGN

- PROJECTED FY 89 START
- 3 YEAR CRUISE (DESTINATION - TEMPLE II)
- 4 YEAR MISSION (EXTENDABLE)
- NO FIXED ORBITAL TIME
  - NO FIXED BATTERY DISCHARGE TIMES
- RTG/SOLAR ARRAY/BATTERY BASELINE

BATTERY SYSTEM DESIGN

- LOAD LEVELLING CAPABII ITY
- 30 V REGULATED BUS
- 32 CELLS PER BATTERY
- CONSTANT POTENTIAL CHARGING
  - CHARGED WITH AVAILABLE EXCESS POWER FROM RTG/SOLAR ARRAY
- PARTIAL RECONDITIONING CAPABILITY

JPL

NiCd RTOP

- OBJECTIVE: DEVELOP PREDICTION MODEL AND ACCELERATED TEST REGIME
- BASIS OF PROGRAM: UNDERSTAND NiCd TECHNOLOGY
- COMPARE: ELECTROCHEMICAL/CHEMICAL PRINCIPLES
  MANUFACTURING PROCESS DATA
  COMPONENT CHARACTERIZATION
  PERFORMANCE/LIFE DATA
- GENERATE MODEL RELATING MATERIAL CHANGES AS A f(RATES, TEMPERATURE, DOD etc.,) TO LIFE AND PERFORMANCE
- MODELS SHOULD BE APPLICABLE TO DIFFERENT MANUFACTURING PROCESS, CELL SIZE AND OPERATING CHARACTERIZATIONS

FIGURE 9. K. CLARK

5-23

"ENERGY STORAGE CONSIDERATIONS FOR A ROBOTIC MARS SURFACE SAMPLER (MARS ROVER)"

ROBERT CATALDO

Bob Cataldo (NASA Lewis Research Center) discussed "Energy Storage Considerations for a Robotic Mars Surface Sampler (Mars Rover)."

Possible power sources for the mission are Radioisotope Thermal Electric Generator (RTG), beamed microwave power, and photovoltaic (PV) (Cataldo [Figure 1]). There are safety concerns with the RTG, and the chance of having beamed microwave power in time for the mission is slight.

The PV solar array will be deployable. It will be susceptible to Martian dust storms (there can be 300 mph winds) although they will not be as significant as they are on Earth because of the low-density atmosphere. Another problem is that the Rover, if it is autonomous, could get "boxed in" behind a hill, causing a shadow to fall across the array thus decreasing power to the rover. (Cataldo [Figure 2]).

A strong motivation for the Rover mission is to bring back 5 kg of rocks and core samples, possibly drilling into the permafrost, possibly to find fossilized types of life. `93/`94 technology will be used for a`98 launch. After the rock sampling is over, the Rover could continue to explore the Martian surface. The Lander could be powered by a solar array, and the Rover could go back and forth using the Lander as a "filling station." The "Trade Analysis" viewgraph, (Cataldo [Figure 4]) shows power system mass vs battery type for a 500W Rover and brings out the conclusion that an RTG system is always a weight saver compared to a PV system. On a volume basis, (Cataldo [Figure 5]) both the integrated and the dedicated fuel cells have the advantages. The advantages of the bipolar nickel hydrogen battery over the sodium sulfur battery include a 35 percent reduction in volume and the demonstrated 10,000- cycle life. The integrated fuel cell and the bipolar battery are primary candidates for this scenario. Cataldo concluded that PV with electrochemical storage can do the job overall for the Rover with the possible need for modifications in operations on a day-to-day basis, because night operation and long troverses would increase the storage weight.

Q. Broderick (GTE): How do you determine the environmental temperature? What are the design criteria?

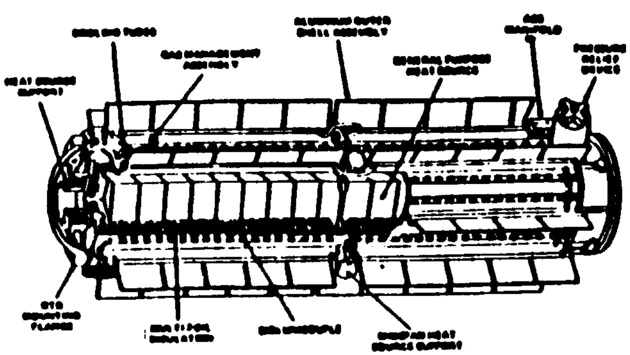
A. Mars has a -40 degree C temperature. This implies the need for heaters. The onboard computer will set the heating requirement as well as other instrumentation. Equatorial temperatures of 20 degrees C may create a need for cooling as well.

Q. Margalit (Tracor Battery): You say temperatures will be lower, but atmospheric densities will also be lower. How will the system lose heat? Have you considered the reduced heat transfer rates in the presence of lower atmospheric density?

A. Thermal management must be looked at, but it hasn't been examined yet.

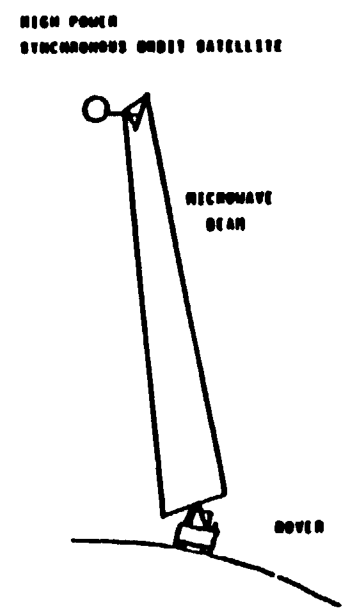
POWER SOURCE/CONVERSION

RTG



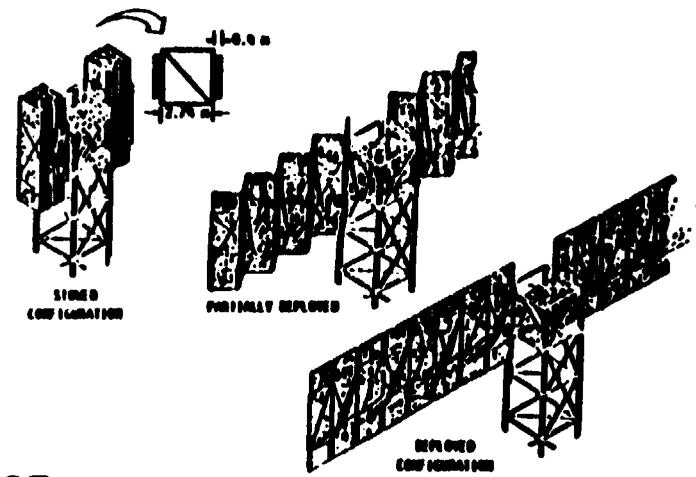
- SAFETY CONCERNS
- AVAILABILITY
- COST
- WEIGHT

MICROWAVE



- EARLY DEVELOPMENT STAGE
- SUPPORT ELEMENT
- LOW EFFICIENCY
- TRACKING
- SAFE
- IMPRACTICAL FOR ROVER POWER LEVEL

PV



- DEPLOYABLE
- HIGH EFFICIENCY
- HIGH SPECIFIC POWER
- SAFE
- SUSCEPTIBLE TO DUST COVERAGE

	RTG	MICROWAVE	PV
EFFICIENCY %	6	2	25
SPECIFIC POWER Kg/Kw	220	TBD	8
SPECIFIC VOLUME l/Kw	340	TBD	35

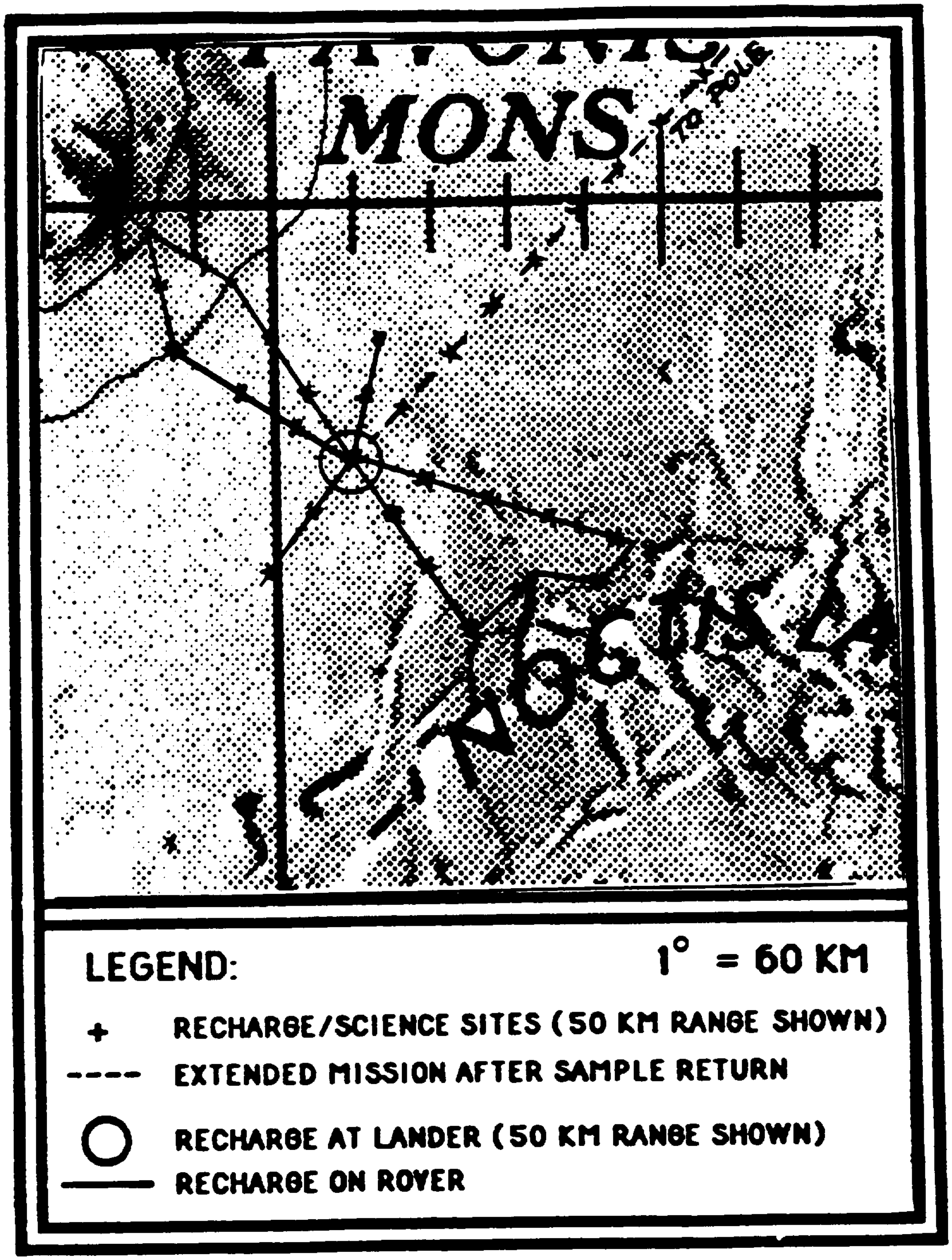
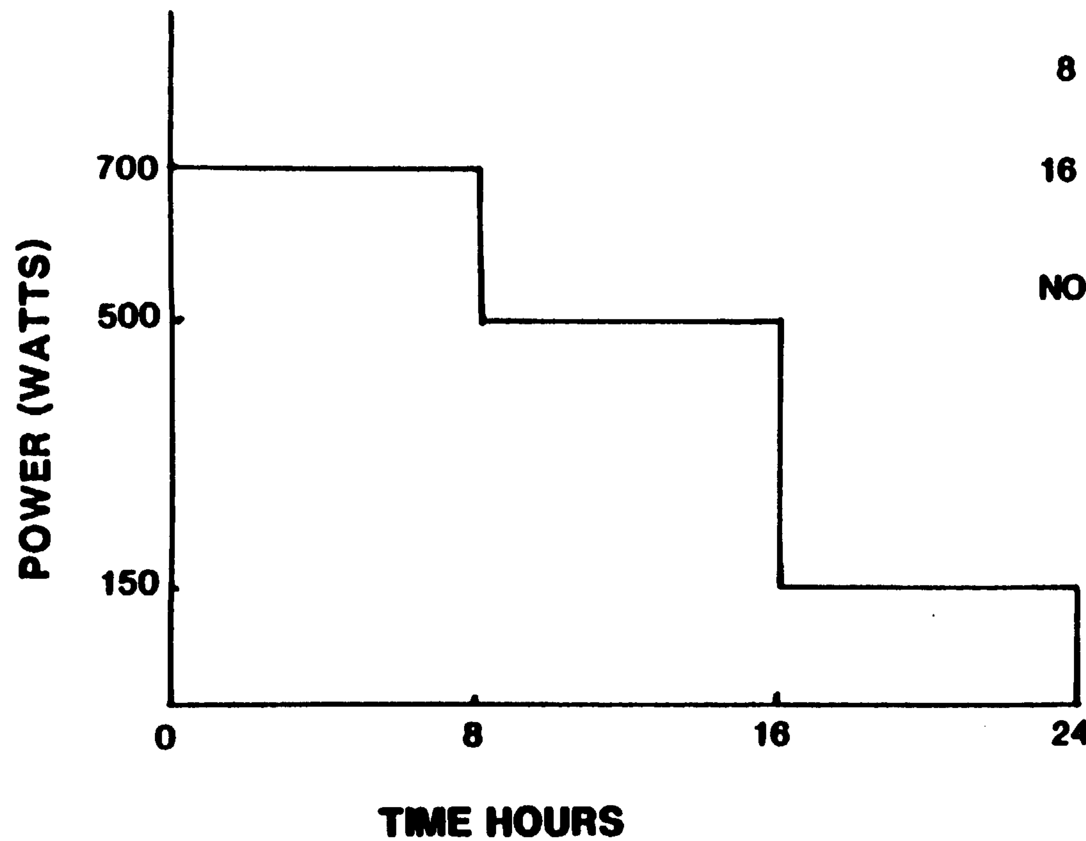


FIGURE 2. CATALDO ROVER TRAVERSING OPTIONS BASED ON POWER SOURCE LOCATIONS

ROVER AVERAGED POWER PROFILE OF PV/STORAGE SYSTEM



SCHEDULE

0 – 8 HR – RECHARGE ENERGY STORAGE

8 – 16 HR – TRAVERSE ROVER ON ENERGY STORAGE

16 – 24 HR – OPERATE SCIENTIFIC INSTRUMENTATION ONLY

NOTE: ROVER OPERATIONS AS SHOWN COULD BE SEGMENTED OVER SEVERAL DAYS

TABLE 1. CATALDO

STORAGE SYSTEMS CHARACTERISTICS

STORAGE	SPECIFIC ENERGY WH/Kg	VOLUME DENSITY L/KW	EFFICIENCY %	CYCLE LIFE	DEVELOPMENT STAGE	PEAK POWER CAPABILITY
Ni-Cd						
SOA	28	43	80	LONG AT LOW DOD	FLIGHT QUALIFIED	MODERATE
ADV	28	43	80	LONG	SOA	MODERATE
$Ni\text{-}H_2$						
IPV	45	67	80	LONG	FLIGHT QUALIFIED	MODERATE
BIPOLAR	50	47	82	LONG	PROTOTYPE	HIGH
Ag-Zn	90	7	85	LOW	FLIGHT QUALIFIED	HIGH
Li-XS	100	27	60	LOW, NONE DEMONSTRATED	DEMONSTRATOR	LOW
Na-S	120	75	85	LOW	PROTOTYPE	HIGH
$PbSO_4$ BIPOLAR	50	43		LOW, NONE DEMONSTRATED	DEMONSTRATOR	HIGH
REGEN. FC						
DEDICATED	190	78	55	LONG	PROTOTYPE	HIGH
INTEGRATED	120	75	55	NONE DEMONSTRATED	DEVELOPMENT	HIGH

FIGURE 3. CATALDO

TRADE ANALYSIS 500W ROVER

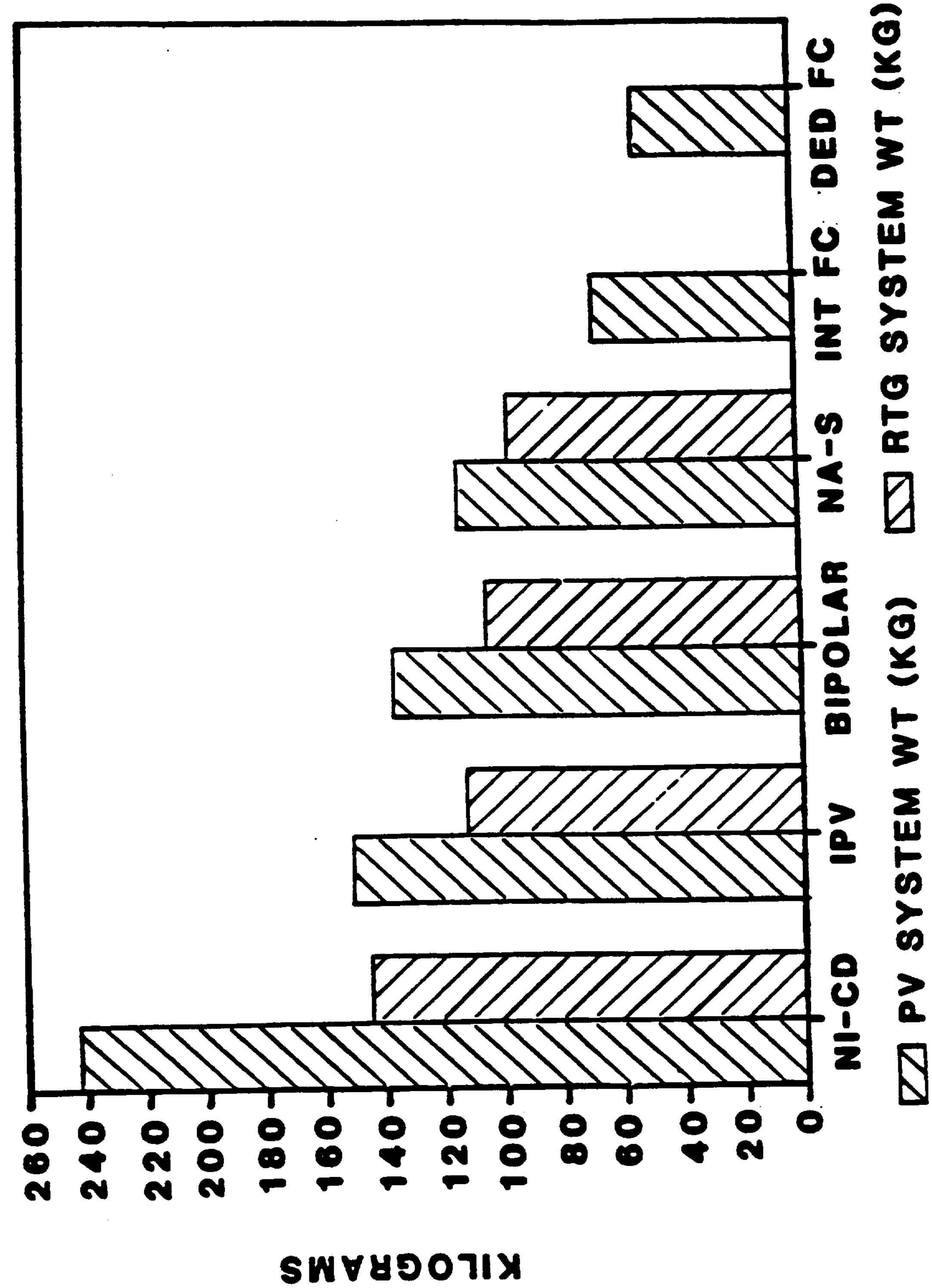


FIGURE 4. CATALDO

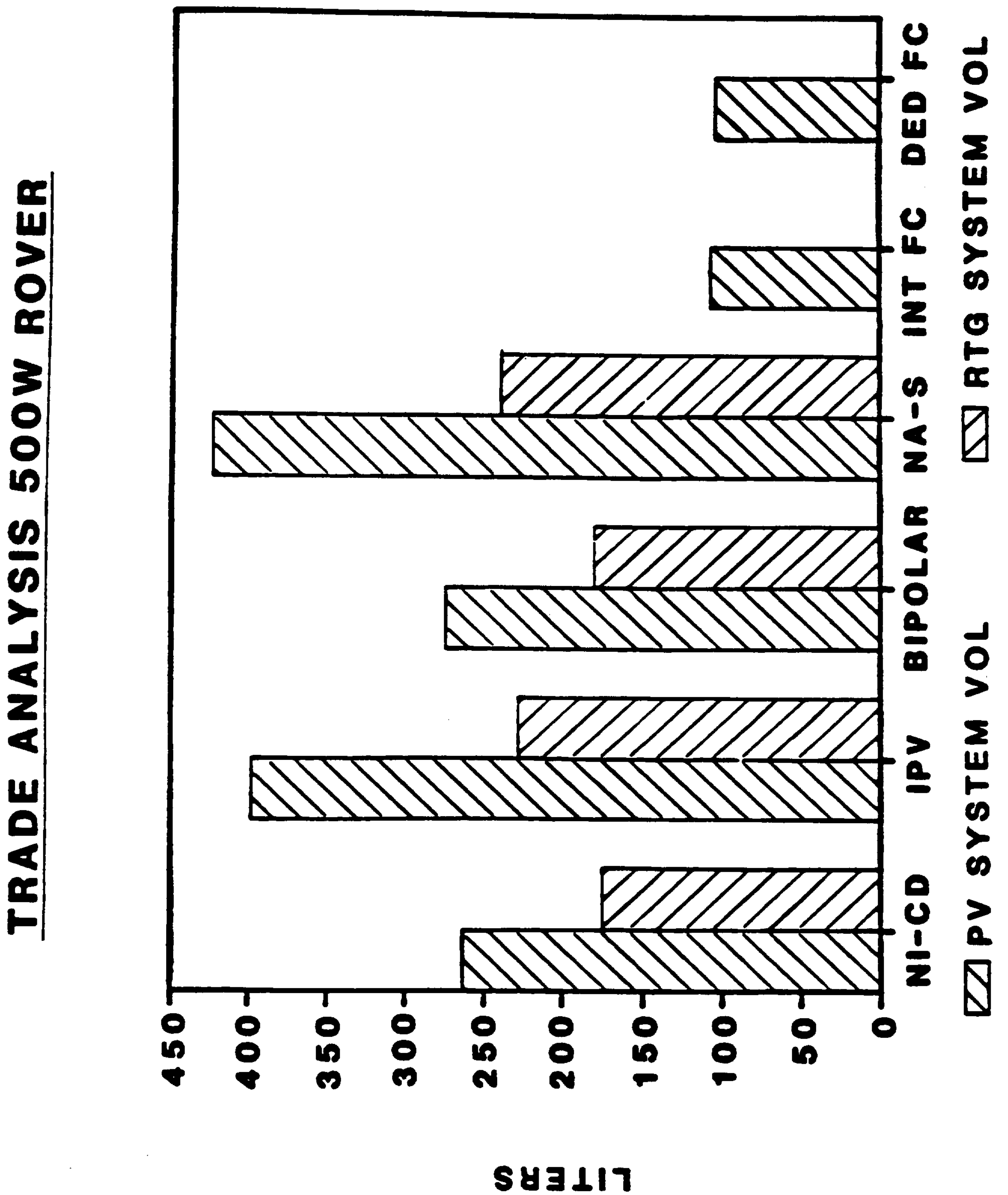


FIGURE 5. CATALDO

ENERGY STORAGE CONSIDERATIONS FOR A ROBOTIC MARS SURFACE SAMPLER

P.M. O'Donnell, R.L. Cataldo,
O.D. Gonzalez-Sanabria
NASA Lewis Research Center
Cleveland, Ohio 44135

INTRODUCTION

Manned exploration of Mars is being proposed by the National Commission on Space for the next century (Ref. 1). To accomplish this task with minimal resupply cost for extended stay times, use of Mars' resources is essential. Methods must be developed to manufacture or extract water and oxygen from elements indigenous to Mars before we send explorers to the planet. Therefore, we must send precursor surveying equipment to determine Mars' resources to a greater extent than is now known from Viking 1 and Viking 2 data. A 1992 launch is planned for the Mars Observer that will contribute greater mapping resolutions and to expand the scientific data base. However, the Observer will not be able to ascertain sub-surface resources such as water in the form of permafrost. A Mars Rover and Sample Return (MR/SR) precursor mission has been identified to accomplish the task of determining surface and sub-surface mineral and chemical resources that will be utilized by future explorers. In addition, geological data of Mars can be obtained to better understand the planet's evolution and possible clues to the history of the solar system. The geological features of Mars include; impact craters, vast canyons, huge volcanoes, shifting sand dunes and polar ice caps.

The proposed rover will provide scientists with the necessary information about abundant resources that would guide the required technology development needed to support a manned Mars infrastructure. This infrastructure would include ecological systems, power generation facilities, manufacturing plants and construction materials. For example, if water in the form of permafrost is present on Mars, the resource would be used for drinking and used in the production of oxygen and hydrogen. These gases would be produced by electrolysis units or possibly by direct thermal decomposition. The oxygen would be used for life support and both gases would be used in a fuel cell energy storage device. The fuel cell plant could provide utility load-leveling in a nuclear power generation system or supply night time power in a photovoltaic power system. In addition, the fuels could be utilized for motive power in a Martian Roving Vehicle (MRV) similar in function to the Lunar Roving Vehicle (LRV) to transport astronauts on the surface of Mars.

The precise scenario for the MR/SR mission is not defined at present. One such scenario is to collect surface mineral samples and drill for sub-surface core specimens.

These samples will undergo in-situ analysis and will be stored on the rover and transported to the Earth Return Vehicle (ERV), which will return about 10 Kgs of samples for further in-depth analysis. The rover could transverse hundred's of Kms during one year while collecting the samples. At first, the rover will travel short distances to collect samples and safely return them to the ERV. As confidence is developed in rover operations, longer, slightly

riskier, terrain will be covered. Once the rover has collected and returned the allotted samples, the ERV will return to earth and the rover will be left behind to explore high risk terrain near canyons, volcanoes and possibly the polar regions. On-board laser instrumentation could be used to scan and analyze areas of geological interest such as canyon and crater walls not readily accessible to the rover. Data of the Martian globe could be recorded and relayed for many years. The actual rover operations plan for both the sample return and extended mission will have a large impact on rover capabilities and the power system supplying power for transversing and scientific instrumentation.

POWER SOURCE AND CONVERSION

Several power source/conversion and location options for the rover have been identified (Figure 1). These include power generation on the lander, Entry Vehicle (EV), Mars Orbiter (MO) and on the rover itself. Power from the lander would require the rover to return to the landing site to recharge the energy storage system, which limits rover excursions to one-half the range of the storage capability. Power from the EV or MO could be beamed microwave or laser power converted from photovoltaic cells on the orbiting spacecraft. The probability of advances in this power transmission technology, to increase efficiency and reduce mass may be beyond the mission technology cut-off date of the 1992-93 time frame.

For on-board rover power, a radioisotope thermoelectric generator (RTG) has

been considered with energy storage to handle peak power demands. However, the availability of isotopes for NASA's use is in question, in addition to high cost, low power density and the politically unfavorable use of reactive materials.

Another method for power generation on board the rover employs rover housed deployable photovoltaic arrays and rechargeable energy storage. The array would be deployable for several reasons, which include:

1) larger area than could be body mounted for faster recharge times
2) sun pointing capability for optimum solar collection
3) Retracted during transversing to increase rover stability and maneuverability
4) Protection during dust storms if necessary.

The rover essentially carries its own motive power energy source and utility, and the deployable array, to supply power for "on-location" recharging, and to perform in-situ scientific analysis. The rover's sampling area is not limited in size by a required return to a fixed "gas-station" as in the scenario of having only recharge capability at the landing site.

Rover operation would occur as follows:

Step 1: deploy array and recharge

Step 2: retract array and transverse to next science site if within range, if not repeat step 1

Step 3: deploy array to power science experiments and recharge.

Figure 2 shows a graphic representation of the two location options for power generation; 1) fixed and 2) portable.

In addition to motive power the rover's energy storage system must have peaking power capability for high power demand operations such as drilling, coring, instrument operation, steep incline maneuvers and maneuvering out of difficult terrain.

STORAGE SYSTEMS

The storage systems considered in this study are listed in Table 1 along with relevant characteristics; the development status at the present time, the peak power capability of the system and cycle life.

Depending on the driving cycle of the rover, instrument power and reserve power, the power system will require about 1.0 to 5.0 kWh of capacity. The driving cycle profiles will be similar to those used for terrestrial electric vehicles. Extensive work was done between 1975 to 1982 on both lead-acid and nickel-zinc battery systems for electric vehicles sponsored by DOE at the NASA Lewis Research Center (Ref. 2).

However, since battery change-out cannot be considered, battery systems with greater charge/discharge cycle capability (>1000 cycles) will be required for the rover. Both nickel-cadmium and nickel-Hydrogen systems have demonstrated many cycles (>10,000) in space use at charge and discharge rates more severe

than required for a rover. Therefore, rover operations could span a 5-10 year life time. State-of-the-art advancements are continuing to be made projecting energy densities of 40-50 Wh/Kg in the near term, and even higher in the future. Battery assembly techniques using bipolar technology in nickel-hydrogen systems have improved high rate pulse performance, thermal management and battery volume and weight. Prototype batteries of this type have demonstrated 1000's of LEO cycles that are one hour charges/half hour discharges, presently with 8000 cycles on an actively cooled 12.0 volt battery and over 1500 cycles on a passively cooled 70.0 volt battery. Increases in cycle life can be projected when considering the less demanding rover operating regime.

The primary fuel cell has been traditionally the power choice for manned space missions because it is compatible with the life support system and has a high energy density. For the rover application one would need to have recharge capability. The regenerative fuel cell was examined for Space Station and both the fuel cell and the electrolyzer have thousands of hours of testing as individual units, however, very limited testing has been done on the two systems operating in a closed cycle unit, referred to as a regenerative fuel cell (RFC).

The regenerative fuel cell with separate hardware for the fuel cell and the electrolyzer is referred to as a dedicated fuel cell system.

Recent studies of fuel cells for GEO missions (Ref. 3) have examined the possibility of combining the fuel cell and electrolyzer into one set of hardware. This system could be a completely passive system with the advantage of increased reliability. This system is just in the development stage.

Among the other systems considered, Na/S has a high energy density of about 100 Whr/kg. It is at the prototype stage of development and could be a candidate for a Mars Rover when developed to its full potential.

The reversible lithium systems and the bipolar lead-acid system are in the laboratory demonstration stage of development and are not considered viable for the proposed technology cut-off date.

ROVER CHARACTERISTICS

Several design options for the rover can be considered depending on the final ambitiousness of the MR/SR mission. The most reliable scenario, with a small increase in versatility over Viking, would involve a small tethered rover that would receive power and control commands via it's umbilical cord. The rover's limited range would tend to increase the lander's capability to touchdown in higher risk terrain that may accompany a potentially rewarding site selection. In addition, the rover would always find its way back to the lander by following it's cord.

Untethered rovers will require a high level of sophistication to accomplish a more ambitious mission. A "high tech" autonomous rover with an extensive range would allow a safe touchdown site selection for the lander while still accessing rewarding, remote science sites nestled in possibly risky terrain. This level of rover capability requires particular consideration for local and global navigation and guidance, data compression, storage and transmission, communications and control, artificial intelligence, propulsion, aerobraking and power conversion and storage.

Local navigation, guidance and hazard avoidance is of particular concern during rover operation due to the 10 to 20 minute delay in the communication link between Earth and Mars. Rover navigation and guidance may need support from a Mars communication infrastructure comprised of low altitude orbiters and aerosynchronous orbiters. Uninterrupted communication at the Martian poles would require a "pole sitter" satellite, which is placed in a libration point high above the planet that only requires small amounts of electric propulsion for station keeping. In addition, a satellite placed in Earth orbit at an Earth-Sun libration point, 60 degrees leading or trailing the Earth, would allow continuous communication during Earth-Mars occultation.

Local navigation options include tele-operation from Earth, based on rover and/or orbiter mounted cameras and autonomous navigation using artificial intelligence and precursor mapping data files. An autonomous system would allow the rover to know where it had been, it's current location, and the return path to the lander. The autonomous system would require more power to

operate, however, it could also save power by retracing it's path back to the lander.

POWER PROFILE

The power profile considered for this study is shown in Figure 3 for the PV/storage option. This scenario allows the rover eight hours of traversing and scientific study, eight hours of scientific study while immobile and eight hours for recharging the energy storage system. The total rover power demand was 500W of which 150W was used to power the scientific instruments. As noted on the figure, the rover operations could be segmented over several days.

TRADE STUDY ANALYSIS AND RESULTS

Two different power system options were evaluated in this paper. One option consisted of an RTG/energy storage device, where the energy storage was used to provide power for peaking and load leveling, and the second one consisting of a photovoltaic array (PV)/energy storage power system where storage is used for motive power. Only storage systems with demonstrated cycle life, peaking capabilities and those that might be available by the technology cut off date were evaluated. These were compared for each power system design and then the two power systems were compared for the advantages and disadvantages of each particular design with respect to total system weight and volume.

Average energy densities were used for the storage systems, since the particular elements of the design have not been established at this point. The energy densities are shown in Table 1. A deployable Galium-Arsenide (GaAs) solar array was used as the basis of comparison with an average power

density of 110 W/m^2 and 10 Kg/KW. A state-of-the-art RTG with a 250W power output and a total system weight of 55 Kg was used.

A total storage capability of 2 KWhr was required for the RTG/storage system. For this small storage capability only batteries were considered. The results of the total system weight and volumes for the different storage systems are shown in Figures 4 & 5. The preliminary analysis shows that Sodium-Sulfur (Na-S) has the lowest total weight and highest volume while the Advanced Nickel-Cadmium (Ni-Cd) has the lowest total volume but highest weight. To reduce both system weight and volume concurrently, the Bipolar Nickel-Hydrogen ($Ni-H_2$) battery would be the storage system of choice.

The PV energy storage power system option needs to provide 5.2 kWhr of storage. This higher storage capacity makes it viable to include regenerative fuel cells as part of our studies. To calculate the total array size and weight the efficiencies of the storage systems were taken into consideration. This accounts for the substantially heavier solar array needed when fuel cells are used. The results show (Figures 4 & 5) that fuel cells will offer definite weight and volume advantages over any other storage system considered. A fuel cell system results in over a 50% weight and volume savings. Looking at the other storage systems, the previously found trends were maintained with the Bipolar $Ni-H_2$ being the next overall system of choice.

When the two power systems are compared the PV/storage system could provide a lighter weight yielding a 30% weight savings. It will also provide a total overall lower volume with a 40% reduction when the system is optimized for both weight and volume. Other system advantages and disadvantages should be considered when a more detailed analysis is performed taking into account the integration, single point failure reliability issue, safety and complexity of these two power systems.

CONCLUDING REMARKS

The power system options examined in this paper for a MR/SR mission show that there are certain weight and volume advantages associated with specific systems.

For the RTG/storage system the bipolar nickel-hydrogen battery and the sodium-sulfur battery are both candidates for storage. The bipolar nickel-hydrogen technology is further advanced, more than 8000 LEO cycles have been demonstrated at the battery level along with peak power capability of 25C. The bipolar nickel-hydrogen storage occupies 35% less volume than the sodium-sulfur battery, while increasing the system weight by only 8% for the same power level. It also has the benefits of low temperature operation and less complexity.

For the PV/storage system, the integrated fuel cell and the bipolar nickel-hydrogen battery are the primary candidates for storage. The fuel cell becomes a more weight and volume efficient option as rover traverse times exceed several hours. Rover power system requirements must be finalized so

that hardware development can be initiated on system components to meet the mission schedule. The bipolar nickel-hydrogen battery is at the prototype technology level while the integrated fuel cell is at the beginning of a development program.

The MR/SR and extended mission can be accomplished utilizing photovoltaics and electrochemical storage. The most promising systems from a weight and volume consideration should be brought to a technology readiness level of six by the 1992-93 time frame in order to be a serious contender for system selection for this mission.

References

1. "Pioneering The Space Frontier", The Report of The National Commission On Space.

2. "State-Of-The-Art Assessment of Electric and Hybrid Vehicle," ERDA, September, 1977.

3. NASA TM 89914, "Regenerative Fuel Cell Study For Satellites In GEO Orbit", Leslie Van Dine, Olga Gonzalez-Sanabria and Alexander Levy, 1987.

"PROGRESS IN NICd AND NIH_2 BATTERIES FOR SPACE USE IN JAPAN"

KOICHI YAMAWAKI

The final speaker for the overview session was Koichi Yamawaki (National Space Development Agency of Japan) who spoke on "Progress in NiCd and NiH_2 Batteries for Space Use in Japan." He listed the NASDA satellite programs from FY `57 to `87. NASDA of Japan has been devoted in the H2O Rocket development Program since 1983. The H20 Rocket would have the ability to put a 2 ton weight satellite in a geostationary orbit. NASADA has initiated The Advance Engineering Satellite named ETS-VI to be launched in 1992. In order to meet ETS-VI mission the batteries are requested to be high performance, having a long life over ten years and also a high energy density. Yamawaki presented a large number of viewgraphs depicting spacecraft plans and related battery research and development plans. The major requirements for a NiCd battery cell are listed in Yamawaki [Figure 4]). This battery will be used in the future for long term low earth orbit satellites. The main factors of the Advanced NiCd batteries are:

- Electrodes - electrochemically deposited substrate high density up to material implementation.
- Diminished substrate corrision for long life.
- Separators - diminished degradation in alkaline solution.

He then discussed the first trials of a new NiCd battery. There was a leakage in the cell due to alkaline corrosion; A new brazing technique has been found to be more effective in combating this corrosion. He found a burst pressure for the NiCd cell of about 100 kg/cm^2 (Yamawaki [Figure 6]). In the organization of Battery Development, last year three battery manufactures in Japan joined the program. As a result of global judgement from this year a decision was made to select Sanyo Electric Co., LTD as the battery integration maker. Under NiCd development electrodes, hermetic terminal, and the cell structure are elements that have been researched since 1985. He followed this discussion with a similar discussion of the NiH_2 battery R and D. NiH_2 will be used for larger capacity applications, (Yamawaki [Figure 11]). Toshiba Corporation is the main contractor for the development of the NiH_2 cell integrator. A nickel hydroxide impregnation system is used (Yamawaki [Figure 12]). There has been some research on dual-pore Hydrogen electrodes, (Yamawaki [Figure 13]).

Results of performance tests for the first trial 35 AH NiH_2 cell appear in (Yamawaki [Figure 18]). A fuel-cell study for the Japanese shuttle is to be finished by next June.

Q. Koehler (Ford Aerospace): What is the status of the ETS-5 NiCd battery?

A. Battery performance is "fine." The battery is in operation and is working well in orbit.

Q. Gentry (Johnson Controls) What has been your experience with the mild steel pressure vessel? Does mild steel work as well in fatigue tests as Inconel?

A. I will address this in the break (Mild steel was his misreading from Yamawaki's OHP.)

Q. Andrasik (NASA Lewis): What material was used for the pressure vessel in the hydrogen cell?

A. Inconel 718.

Q. Youngblood (GE America): What reconditioning procedure was used for the NiCd cells on ETS-6?

A. It was the same procedure used for ETS-5. It's not so special.

PROGRESS IN Ni-Cd AND $Ni-H_2$ BATTERIES

FOR SPACE USE IN JAPAN

NATIONAL SPACE DEVELOPMENT AGENCY

OF

JAPAN

FIGURE 1. YAMAWAKI

DEVELOPMENT ORGANIZATION OF HIGH PERFORMANCE Ni-Cd BATTERY

PLANNING/PROJECT CONTROL	NASDA TSUKUBA SPACE CENTER
CELL INTEGRATION	SANYO ELECTRIC CO., LTD.
ELECTRODES	SANYO ELECTRIC CO., LTD.
SEPARATOR	JAPAN VILENE CO., LTD.
HERMETIC TERMINAL	TOSHIBA CORPORATION
CELL STRUCTURE	THE YOKOHAMA RUBBER CO., LTD.

FIGURE 2. YAMAWAKI

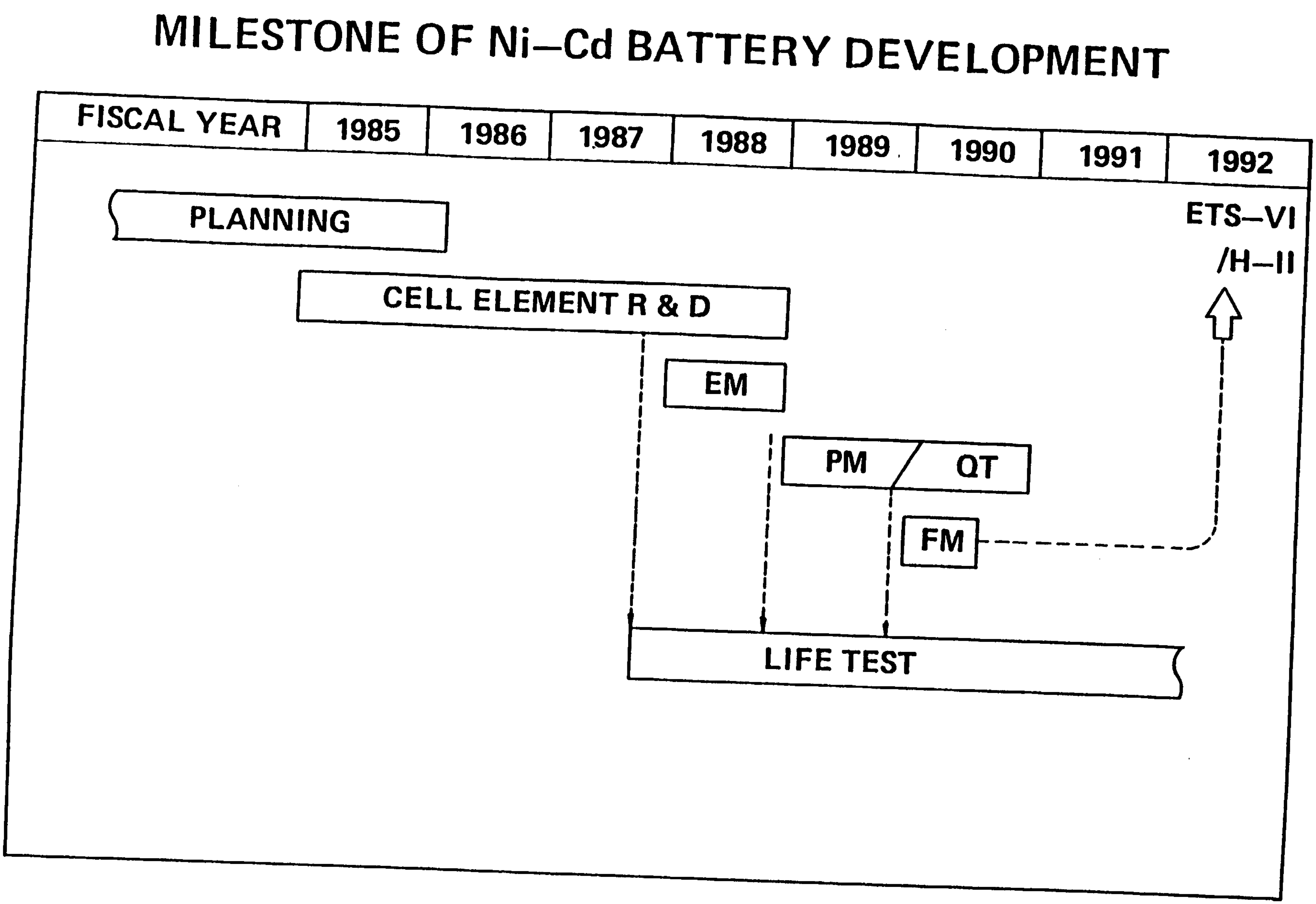
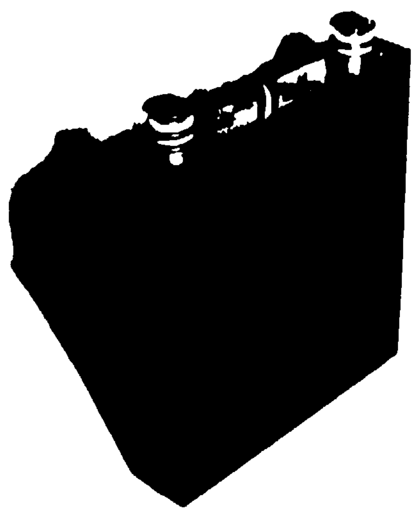


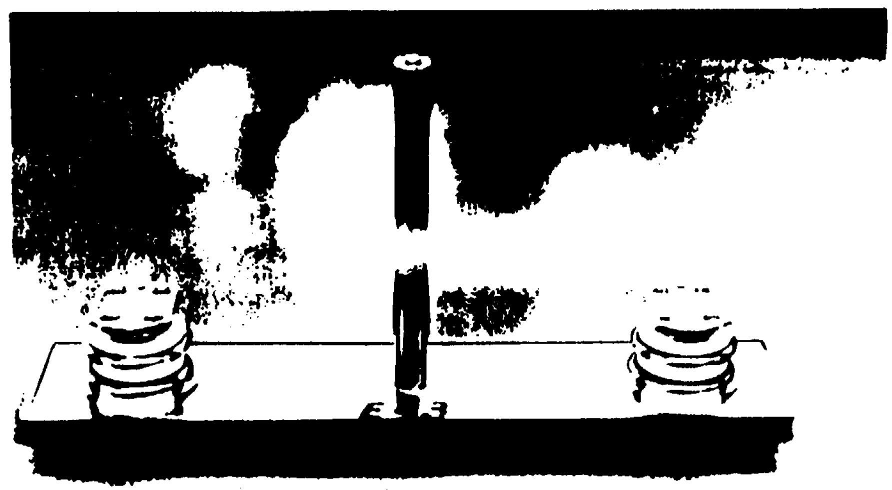
FIGURE 3. YAMAWAKI



Ni-Cd BATTERY CELL MAJOR REQUIREMENTS

CAPACITY	:	35 AH
MISSION	:	10 YEARS
		1000 CYCLES
DOD	:	50 %
ENERGY DENSITY	:	40 WH/KG
LAUNCH YEAR	:	1992

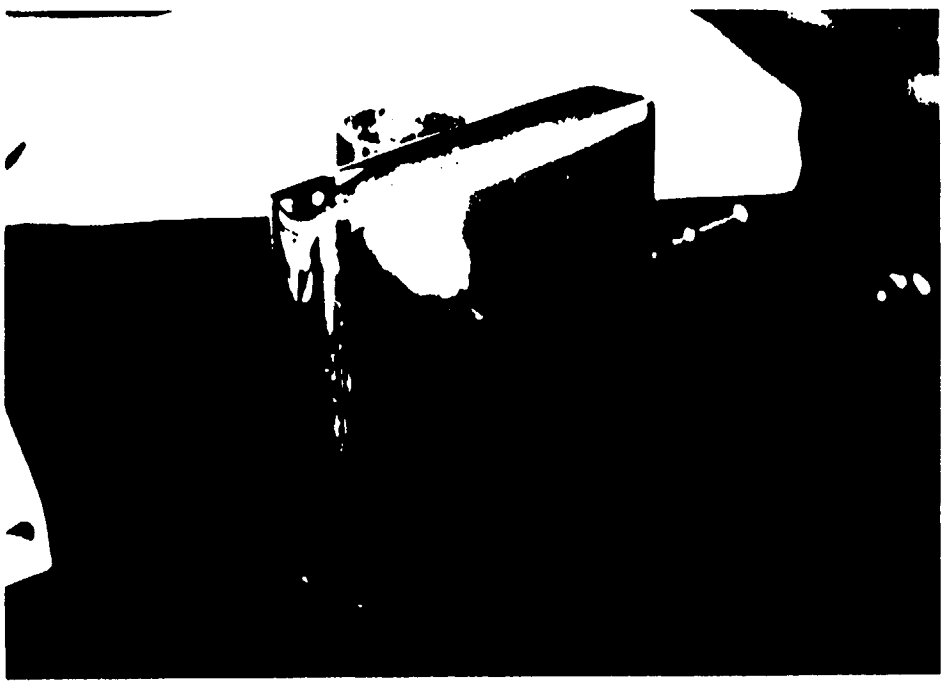
FIGURE 4. YAMAWAKI



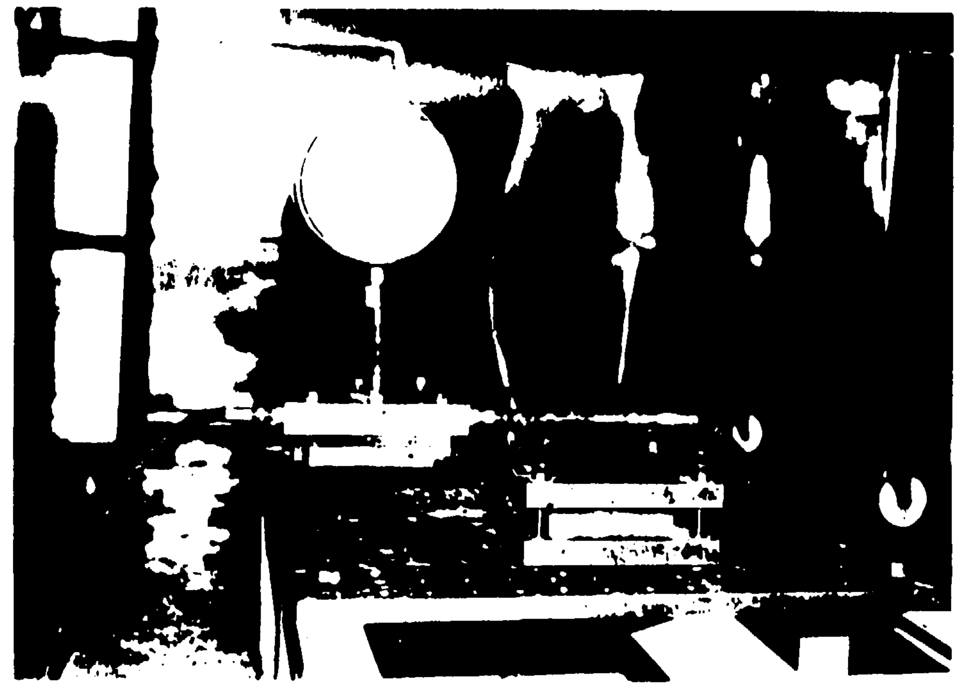
Ni—Cd CELL TERMINAL ASSEMBLY

FIGURE 5. YAMAWAKI

Ni-Cd CELL BURST PRESSURE TEST

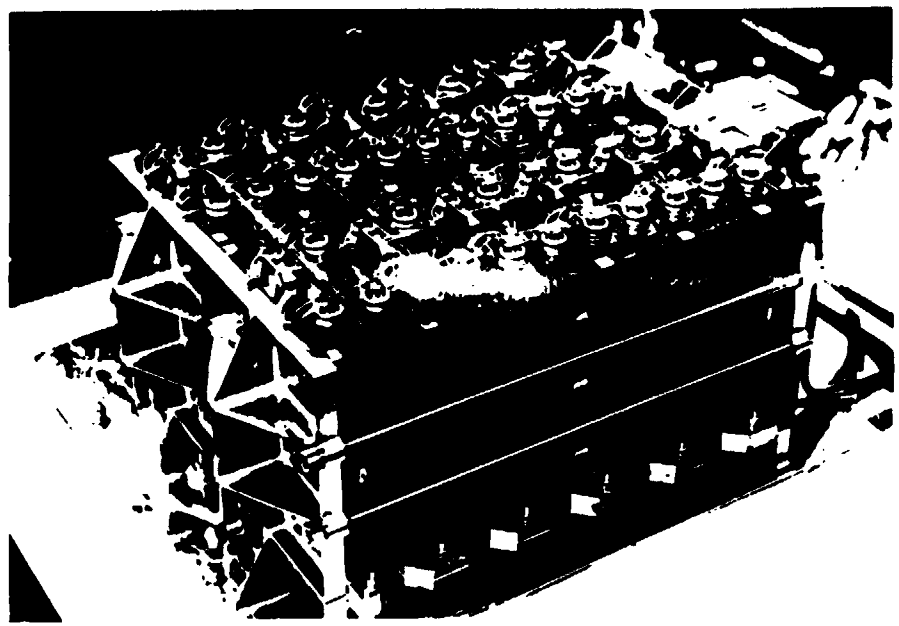


Ni-Cd CELL CASE
AFTER BURST PRESSURE TEST



TEST CONFIGURATION

FIGURE 6. YAMAWAKI



VIBRATION TEST OF BREADBOARD Ni-Cd BATTERY

FIGURE 7. YAMAWAKI

BATTERY TEST FACILITIES IN TSUKUBA SPACE CENTER

BATTERY TEST CONTROLLER

TEST CHAMBERS

FIGURE 8. YAMAWAKI

DEVELOPMENT ORGANIZATION OF $Ni\text{-}H_2$ BATTERY

PLANNING/PROJECT CONTROL	NASDA TSUKUBA SPACE CENTER
CELL INTEGRATION	TOSHIBA CORPORATION
ELECTRODES, ETC.	TOSHIBA CORPORATION
PRESSURE VESSEL	ISHIKAWAJIMA-HARIMA HEAVY INDUSTRIES CO., LTD.
HERMETIC TERMINAL	NIPPON VALQUA INDUSTRIES, LTD.

FIGURE 9. YAMAWAKI

MILESTONE OF $Ni-H_2$ BATTERY DEVELOPMENT

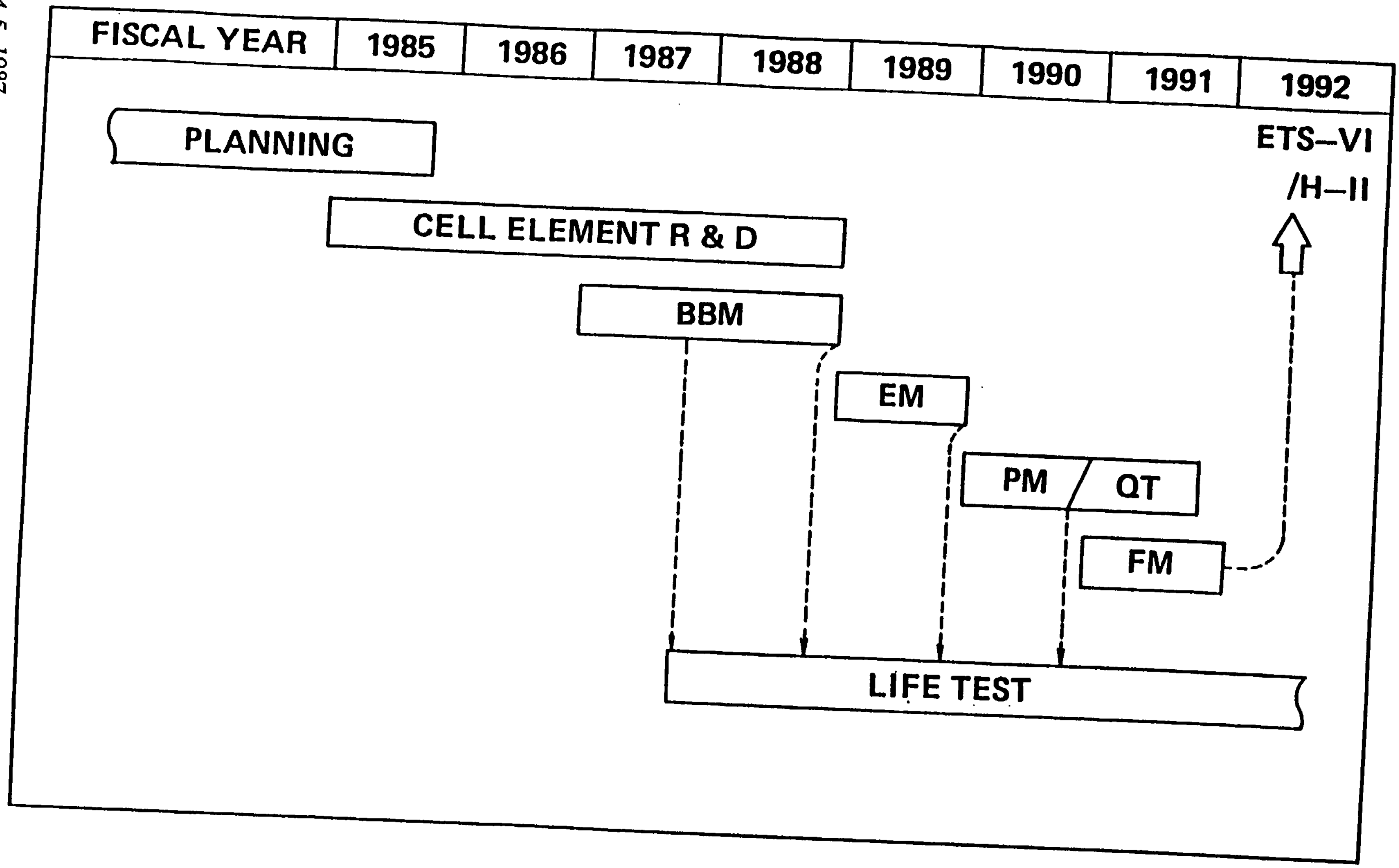
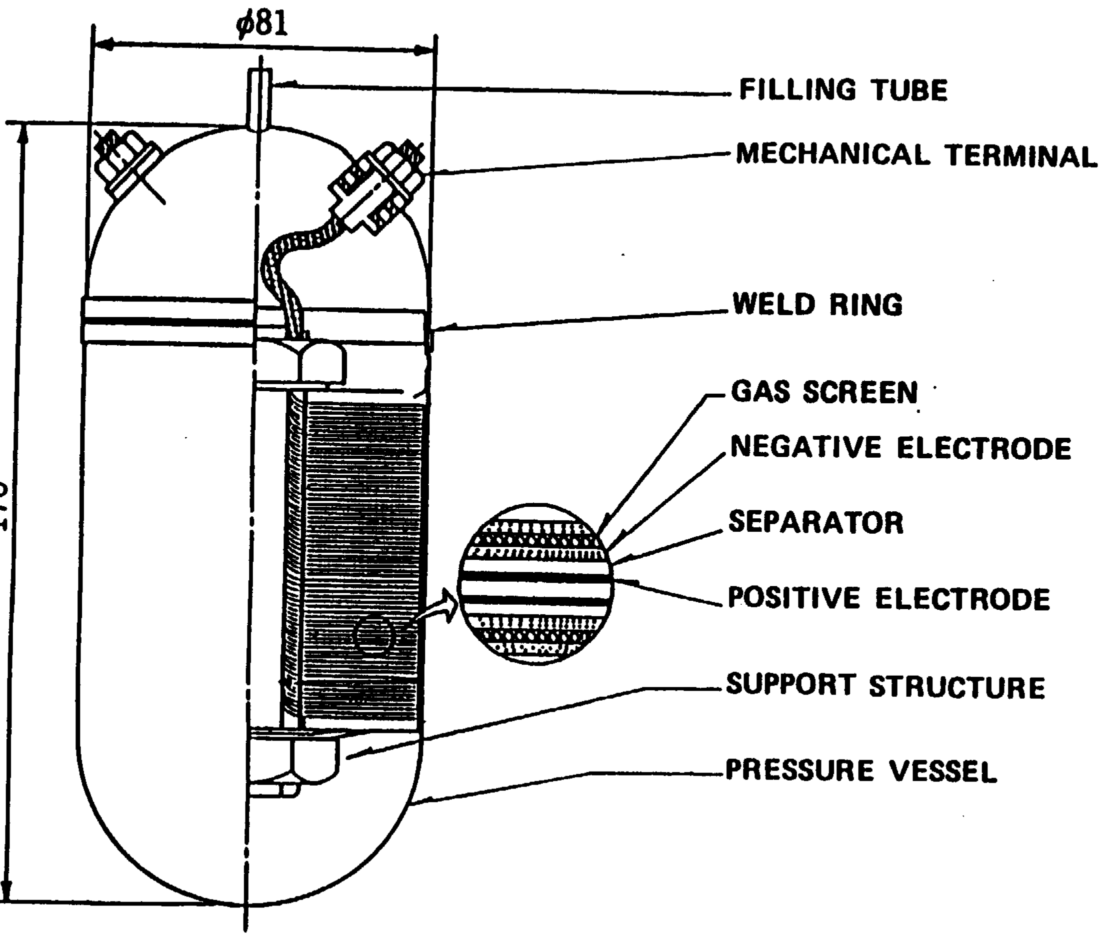


FIGURE 10. YAMAWAKI

CONFIGULATION OF $Ni-H_2$ CELL



MAJOR REQUIREMENTS

CAPACITY	:	35 AH
MISSION	:	10 YEAR
DOD	:	80 %
WEIGHT	:	1000g
LAUNCH YEAR	:	1992

FIGURE 11. YAMAWAKI

COMPARISON OF $Ni(OH)_2$ IMPREGNATION METHODS

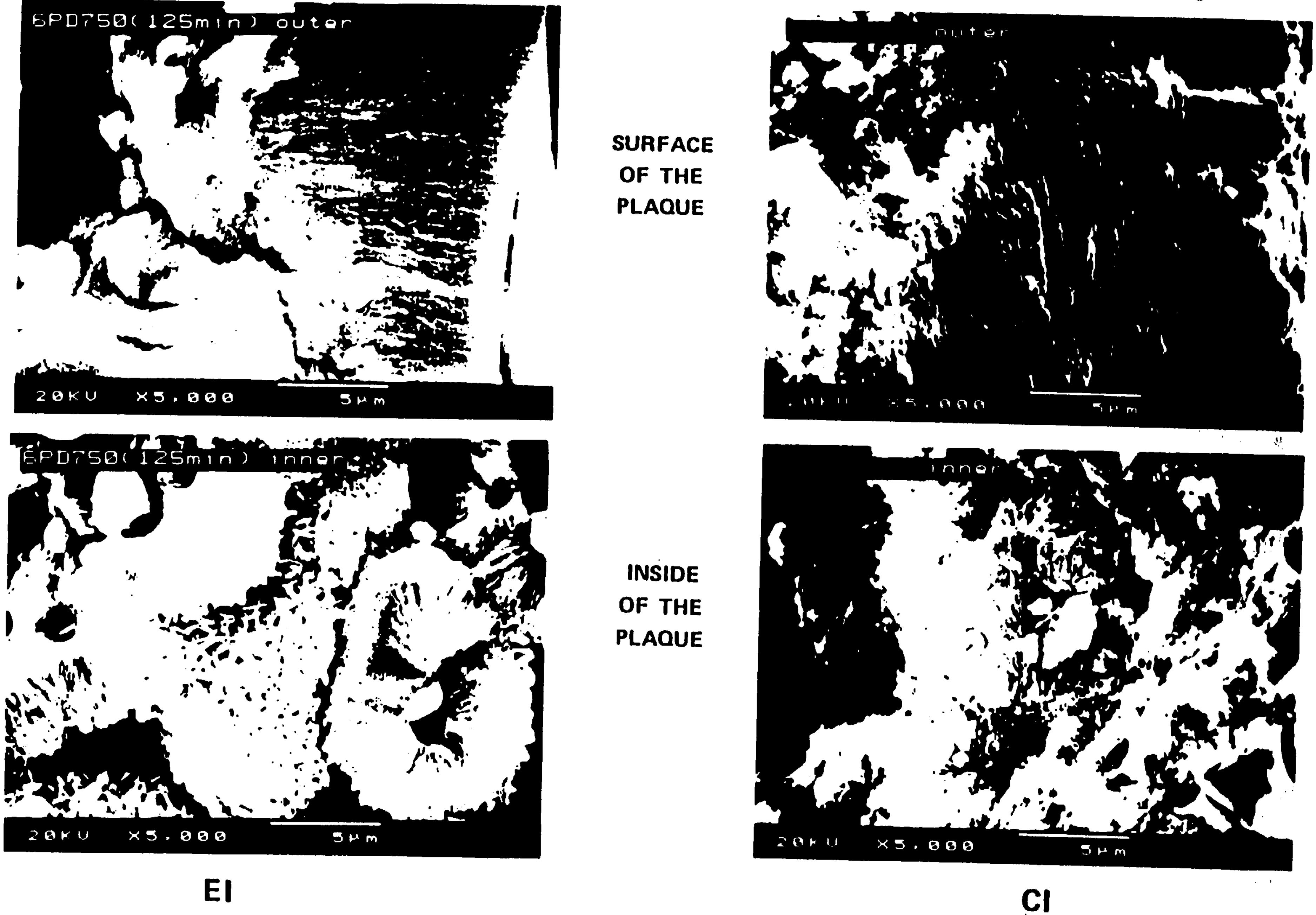
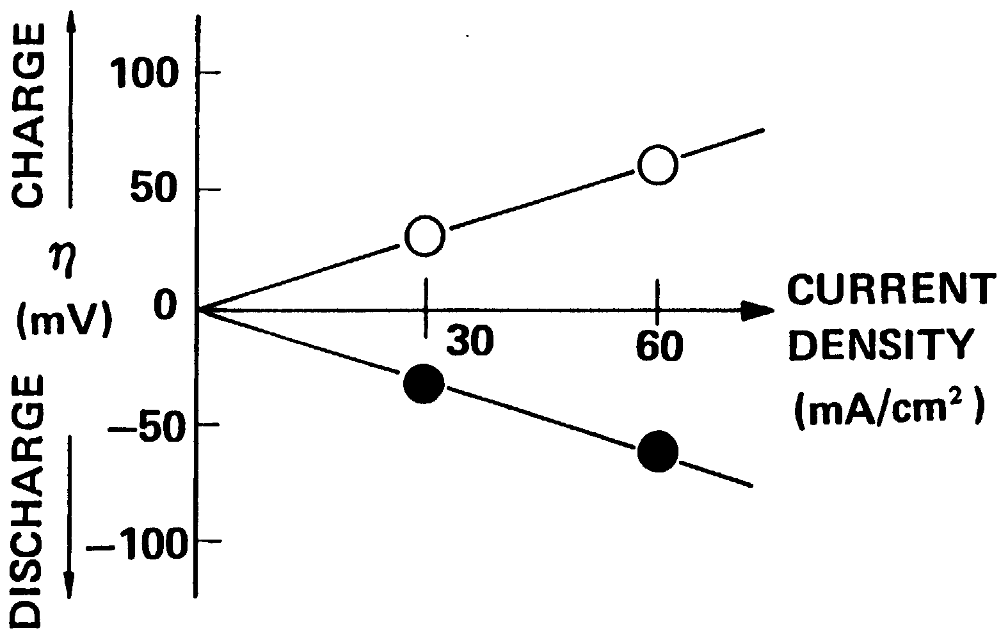
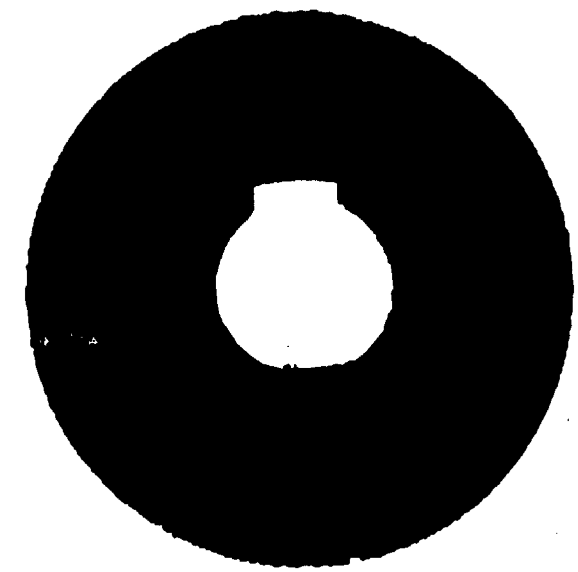


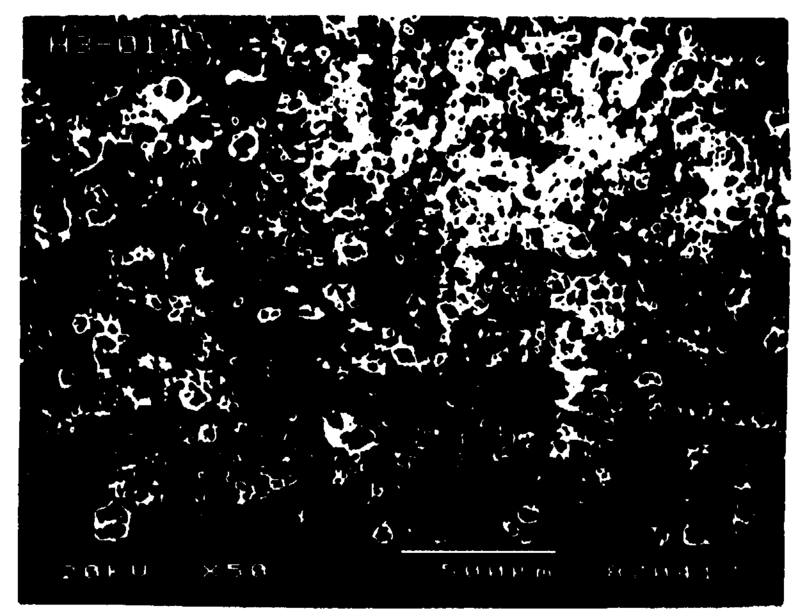
FIGURE 12. YAMAWAKI

H_2 ELECTRODE (DUAL – PORE ELECTRODE)



TYPICAL I – η CHARACTERISTICS





EVALUATION TEST OF CELL ELEMENTS

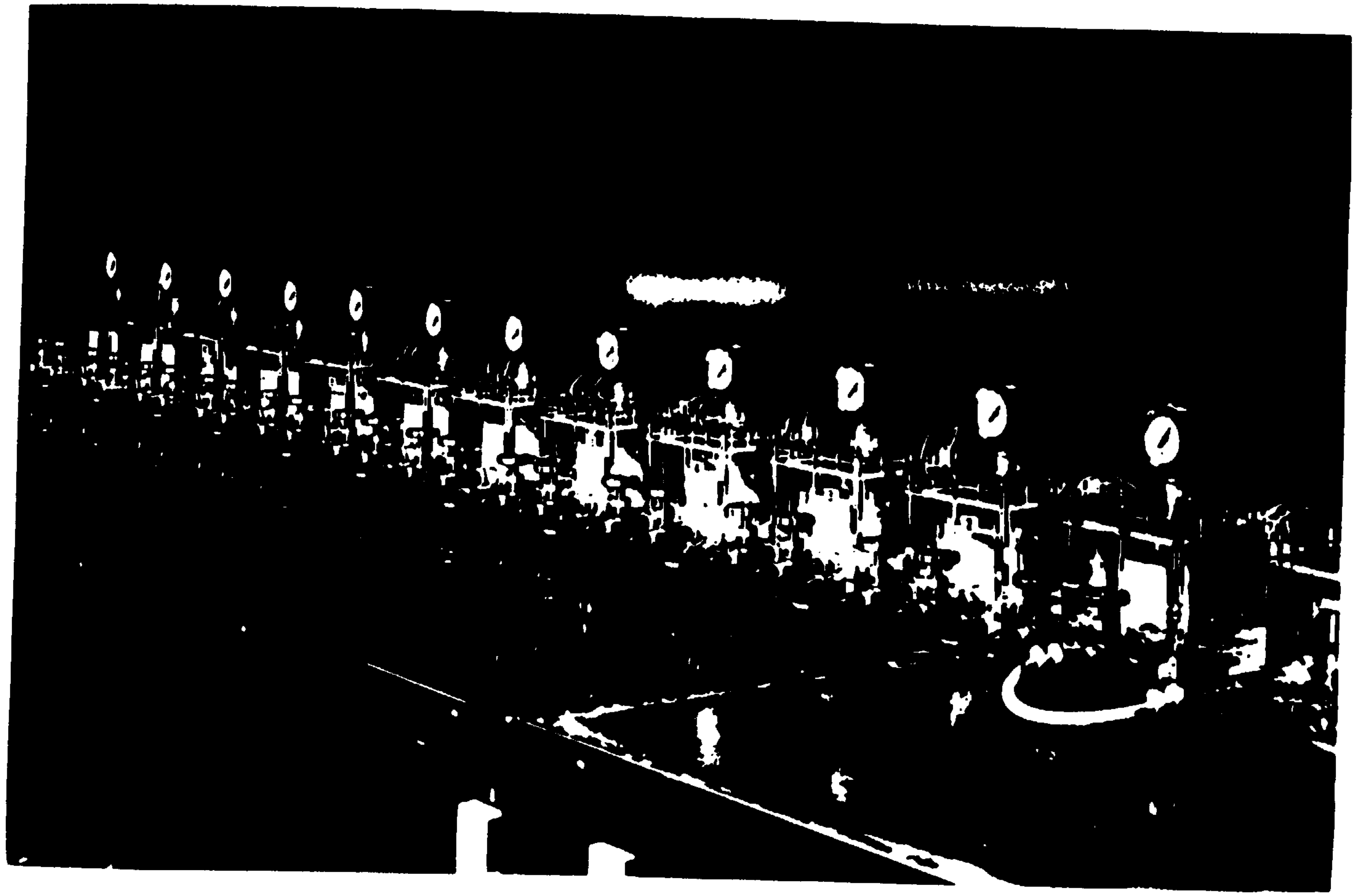
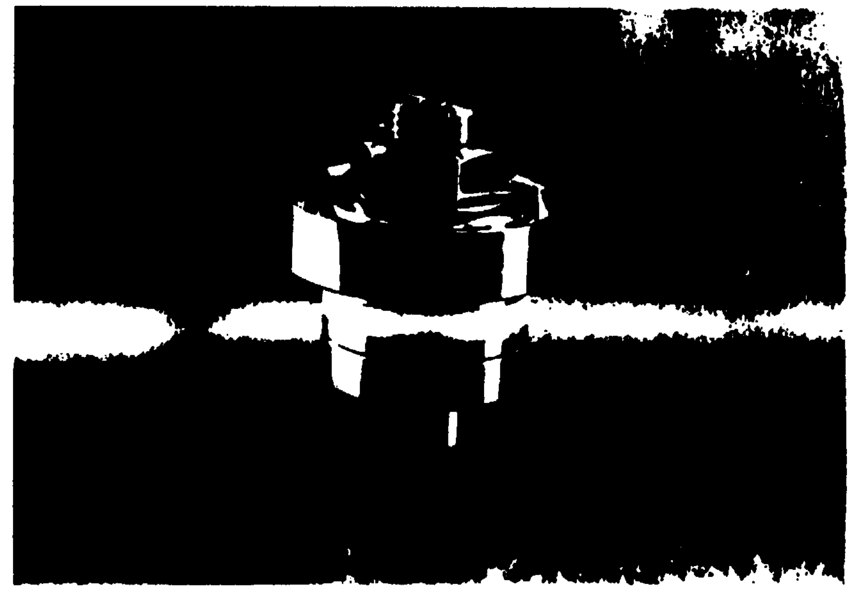


FIGURE 14. YAMAWAKI

ORIGINAL PAGE IS
OF POOR QUALITY

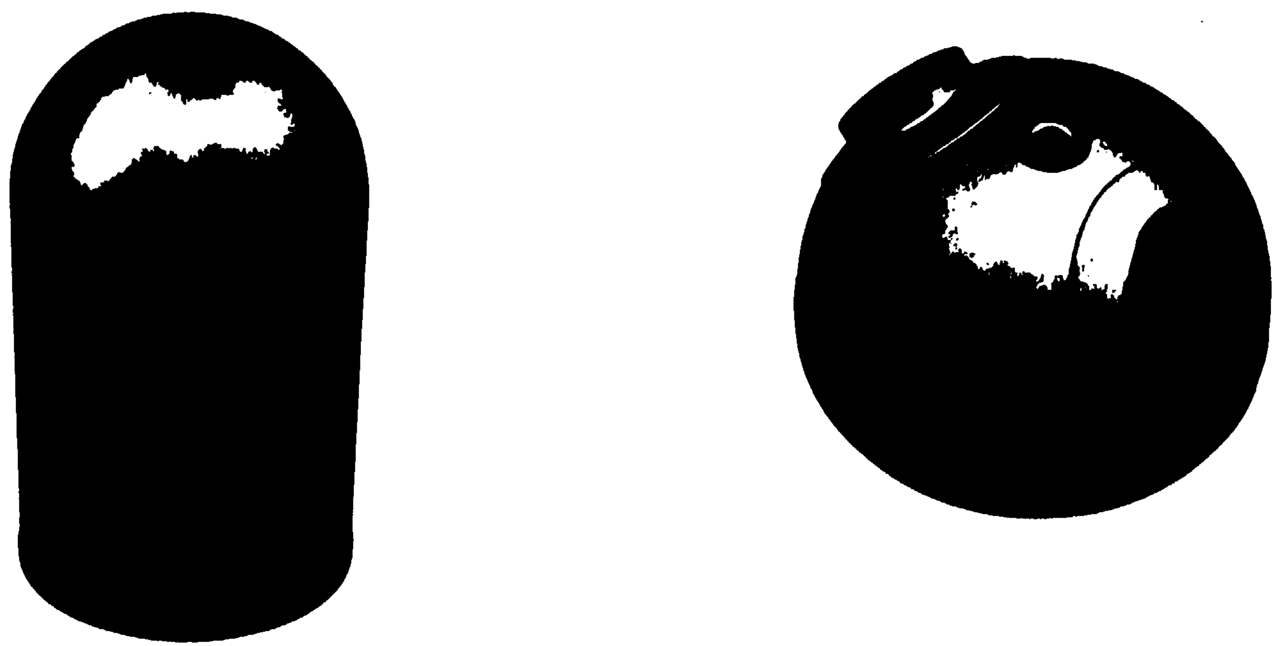
TERMINAL ASSEMBLY



MECHANICAL SEAL TERMINAL with Spring—Energized Elastic Metal Gasket

FIGURE 15. YAMAWAKI

PRESSURE VESSEL OF 35AH $Ni-H_2$ CELL



LOWER PORTION

UPPER PORTION

FIGURE 16. YAMAWAKI

FIRST TRIAL OF 35AH Ni—H_2 CELL

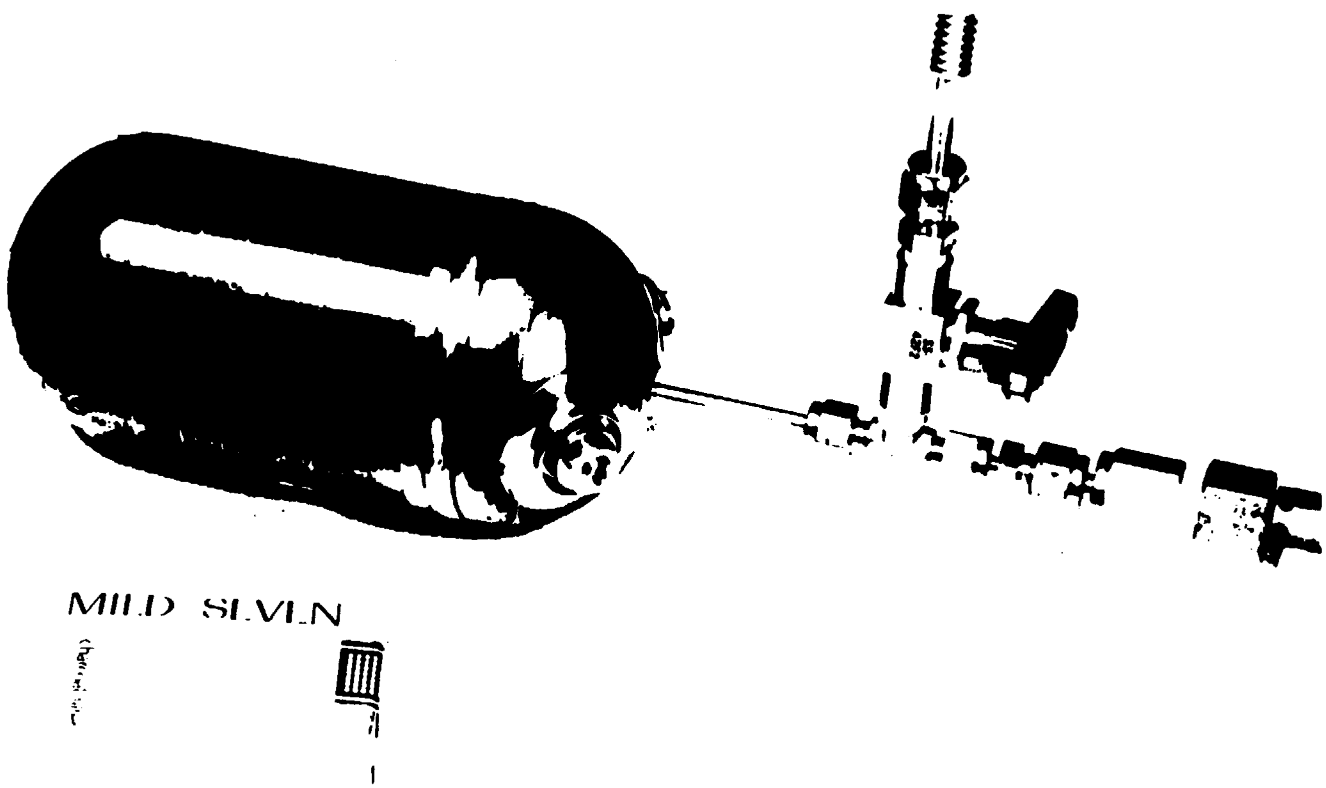
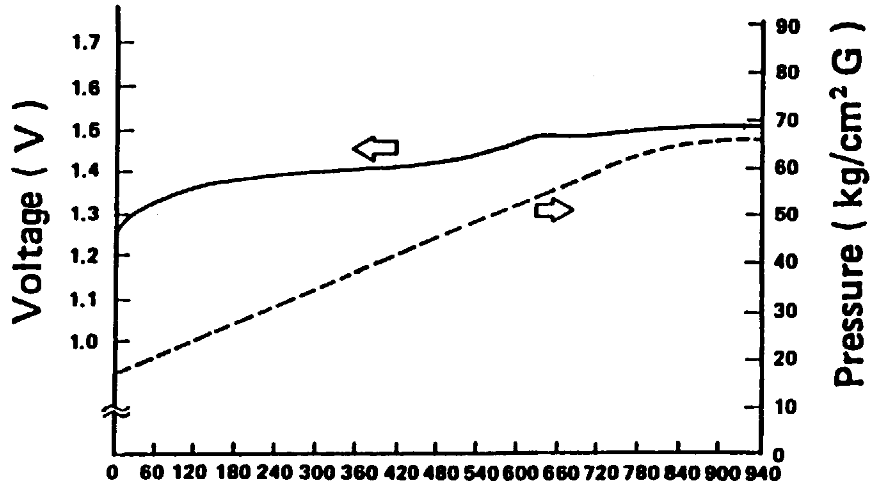


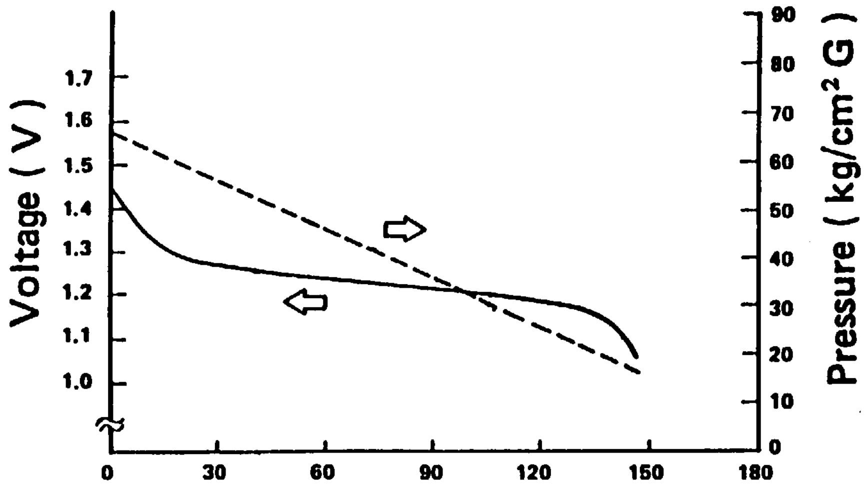
FIGURE 17. YAMAWAKI

PERFORMANCE OF THE FIRST TRIAL CELL



CHARGE PERFORMANCE

CHARGE RATE: C/10



DISCHARGE PERFORMANCE

DISCHARGE RATE: C/2

FIGURE 18. YAMAWAKI

SESSION II

LITHIUM

Chairman: Dr. Gerald Halpert, JPL

"THE USE OF LITHIUM BATTERIES IN SPACE"

GERALD HALPERT

After the break Gerald Halpert of JPL took over as chairman of the Lithium session.

Gerald Halpert (JPL) gave the presentation "The Use of Lithium Batteries in Space" in which he listed past applications of lithium batteries along with technology issues, goals, and future NASA plans.

The obvious advantages of lithium batteries over other chemical energy storage devices include higher specific energies, higher volumetric energy density, and longer activated shelf life. All these result in a battery that is lighter, smaller, and longer lasting during the cruise phase.

The lithium batteries have been used in:

Long Duration Exposure Facility (LDEF) - $LiSO_2$

Galileo Probe - $LiSO_2$

Shuttle - There are several shuttle applications which use the lithium system. They include helmet light, EMU TV Camera, Mineoscope, various recorders, etc.

Centaur Launch Vehicle - $LiSOCl_2$

Due to inherent weight/volume advantages, the lithium batteries can be used in many JPL applications. The planetary observer missions need light weight/low volume batteries. Although RTG's are satisfactory for the providing continuous power, they are inadequate for pulse power. Probes are ideal applications for primary lithium batteries.

Halpert presented a NASA OAST chart on future spacecrafts which may require lithium chemistry. The chart covers from 1980's to 2010's, enveloping transportation systems, spacecrafts, and large space systems.

For the specific goals of lithium primary cells, a $LiSOCl_2$ cell be developed by EOFY '88 with 300 Ah/Kg, activated storage life of 10 years, and safe operation at -40 degrees C. Similarly, for the secondary cells, 100-125 Wh/Kg energy density will be demonstrated by 1992. This reflects 4 to 6 times that of the state-of-the-art rechargeable systems. By 1997, 150-200 Wh/Kg will be demonstrated, and by 2002, 200-500 Wh/Kg. The system shall be capable of safe operations, and for 1000 cycles (GEO). Halpert envisions using primary lithium cells on the launch vehicles such as Centaru and IUS; standby emergency

equipment such as Crew Emergency Return Vehicle; on astronaut power such as MMU and EMU; on probes such as Saturn Orbiter Titan Probe; and experiments such as GAS.

A road map outlining the development of primary $LiSOCl_2$ cell was presented for years 1982 to 1992. By that time, a $LiSOCl_2$ cell with 300 Wh/Kg and 10 year active storage life will be developed.

Halpert envisions using secondary lithium cells on planetary missions for prime power and RTG segmentation. He also sees the lithium usage for GEO orbits as well as for mobile equipment vehicles such as a rover. The lithium system may of course be used in the equipment used by an astronaut.

Like for the primary system, a road map outlining the development of rechargeable lithium cell was presented for years 1984 to 1994. By the time, a lithium cell with 100 Wh/Kg and 10 year active storage life will be developed.

Halpert presented various charts on specific programs and other JPL development works on lithium cell. A chart on technology issues and developments for use of $LiTiS_2$ was presented. Various options which may require the usage of lithium cells for Mars Sample Return mission were summarized in one of the charts.

Halpert concluded by saying that because of lighter weight, smaller volume, and long storage life requirements, lithium batteries are becoming a viable alternative as its technology and safety are improved.

Q. ______: Are we pushing lithium into crystal? Lithium is thermodynamically unstable. Going into and out of cathodes depends on kinetics. Can we go in and out at high rates?

A. The limiting electrode has been lithium. TiS_2 electrodes are being studied. We have four years to go.

Q. Mackowski (McDonnell Douglas): Is the work taking place at JPL?

A. The Li and NiCd work takes place at JPL. Lewis does the fuel cell and NiH_2 work.

THE USE OF LITHIUM BATTERIES IN SPACE

GERALD HALPERT AND S SUBBARAO
ELECTROCHEMICAL POWER GROUP
JET PROPULSION LABORATORY

Presented at the NASA Battery Workshop
November 1987

FIGURE 1. HALPERT

OVERVIEW

PAST APPLICATIONS

TECHNOLOGY ISSUES AND GOALS

ROLES FOR LITHIUM PRIMARY BATTERIES

ROLES FOR LITHIUM SECONDARY BATTERIES

NASA PLANS

FIGURE 2. HALPERT

LITHIUM BATTERIES

STRENGTHS

HIGHER SPECIFIC ENERGY

HIGHER VOLUMETRIC ENERGY DENSITY

LONG ACTIVATED SHELF LIFE

RESULTS IN

LOWER WEIGHT

SMALLER VOLUME

EXTENDED CRUISE CAPABILITY

FIGURE 3. HALPERT

TODAYS APPLICATIONS

LONG DURATION EXPOSURE FACILITY (LDEF) ($Li-SO_2$)

GALILEO PROBE ($Li-SO_2$)

SHUTTLE - Helmet Light
SHUTTLE - EMU TV Camera
SHUTTLE - Mineoscope
SHUTTLE - Cassette Data Tape Recorder
SHUTTLE - Accelerometer Recorder
SHUTTLE - Microgravity Accelerometer
SHUTTLE - Other

LAUNCH VEHICLES - CENTAUR ($Li-SOCl_2$)

FIGURE 4. HALPERT

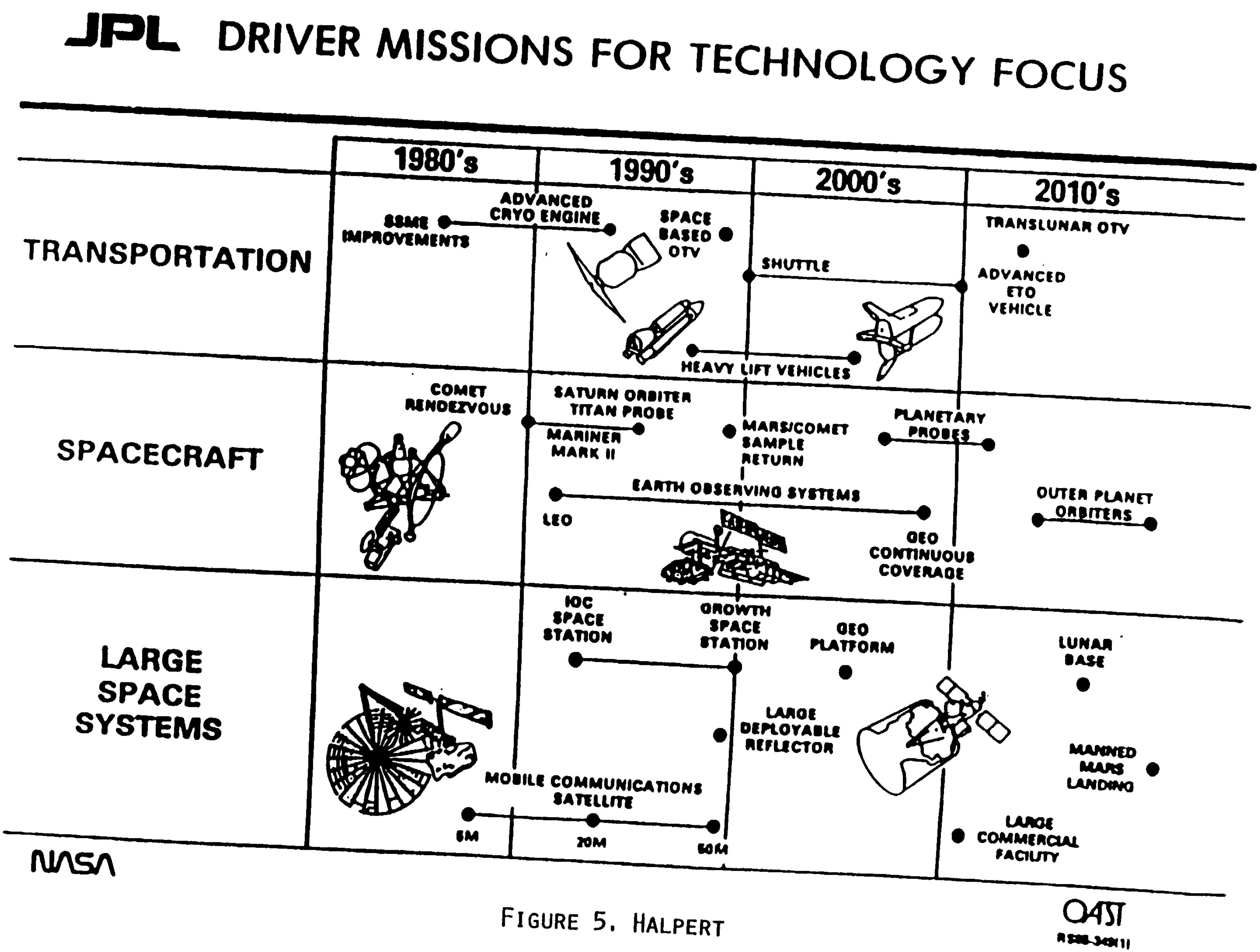


FIGURE 5. HALPERT

KLA-3

GOALS AND OBJECTIVES

PRIMARY CELLS AND BATTERIES:

- TO DEMONSTRATE BY EOFY'88 A HIGH SPECIFIC ENERGY ELECTROCHEMICAL STORAGE DEVICE (LI-$SOCl_2$)
  - SP. ENERGY 300 WH/kg (SOA Ag-Zn = 100 WH/kg)
  - ACTIVATED STORAGE 10 years (SOA Ag-Zn = 6 MO.)
  - SAFE OPERATION AT EXTREME ENVIRONMENTS (-40°C)

SECONDARY CELLS AND BATTERIES:

- TO DEMONSTRATE HIGH SPECIFIC ENERGY RECHARGEABLE CELLS
  - 100 - 125 WH/kg BY 1992 (4-6 x SOA)
  - 150 - 200 WH/kg BY 1997 (6-8 x SOA)
  - 200 - 500 WH/kg BY 2002 (10-20 x SOA)
    (SOA NI-Cd = 28 WH/kg, SOA NI-H_2 = 45 WH/kg)
  - SAFE OPERATION IN EXTREME ENVIRONMENTS
  - 1000 CYCLE OPERATION (10 years)
  - LONG-TERM CHARGED ACTIVE STORAGE LIFE (10 years)
    (SOA NI-Cd AND NI-H_2 = 6 MO.)

FIGURE 6. HALPERT

TECHNOLOGY ISSUES

- EMERGING PLANETARY AND EARTH-SCIENCE MISSIONS FACE:
  - ENERGY SHORTFALL: LOW WH/kg (FLIGHT SOA ~ 100 WH/kg PRIMARY)
    (SOA ~ 28 WH/kg RECHARGEABLE)
  - LONG CRUISE: > 10 yr MISSIONS
  - HOSTILE ENVIRONMENTS: RADIATION, THERMAL
  - SEVERE MASS/VOLUME CONSTRAINTS: LV PERFORMANCE PROBLEM
  - INCREASED OPERATIONAL LIFE: 1000 CYCLES - 10 yrs

FIGURE 7. HALPERT

FUTURE ROLES FOR LITHIUM PRIMARY BATTERIES

LAUNCH VEHICLES
(Centaur, IUS)

STANDBY EMERGENCY EQUIPMENT/VEHICLES
(Crew Emergency Return Vehicle)

ASTRONAUT POWER
(MMU, EMU)

PROBES
(Saturn Orbiter Titan Probe)

EXPERIMENTS
(Get-A-Way Special)

BALLOONS

BEACONS
(SARSAT)

FIGURE 8. HALPERT

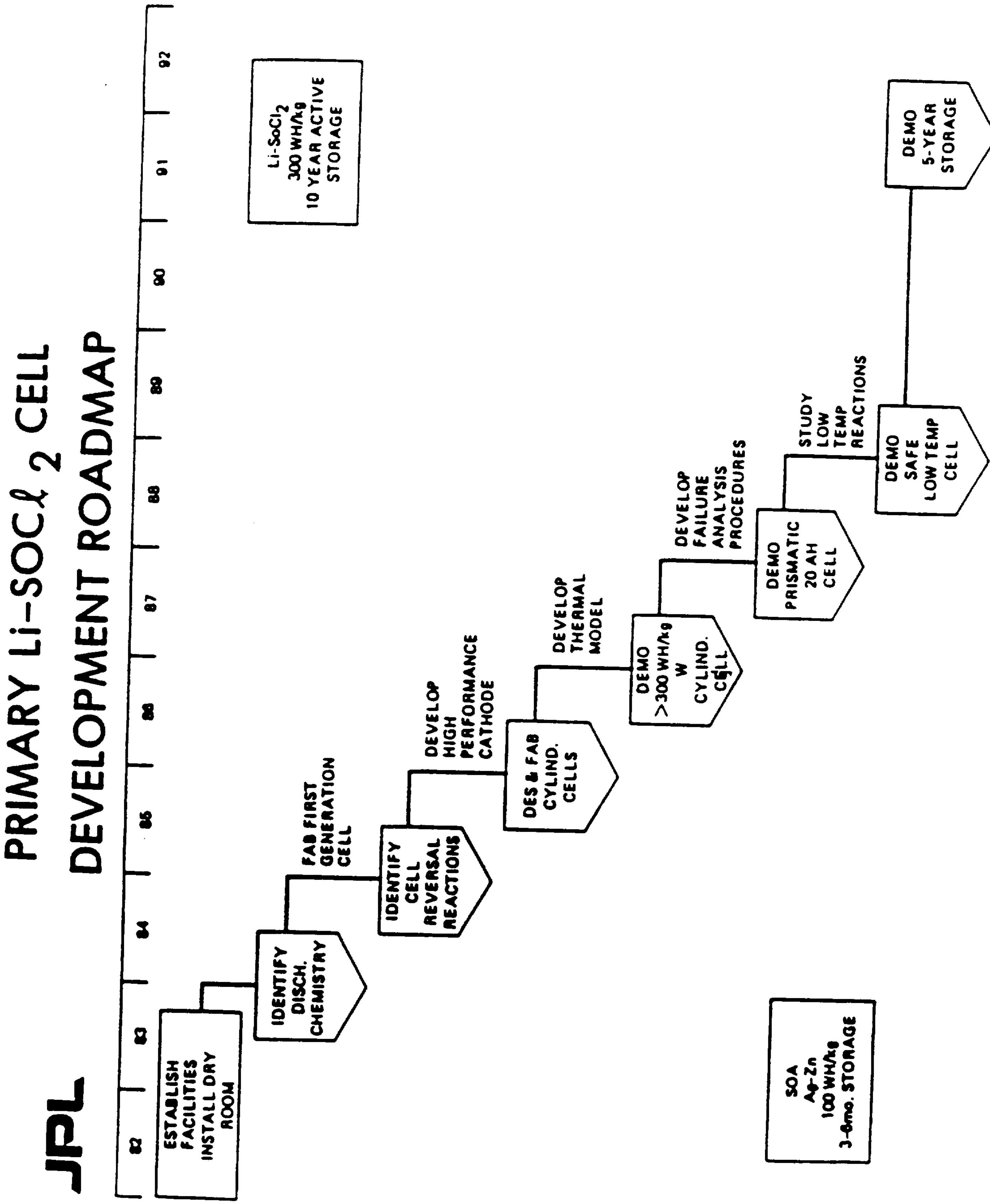


FIGURE 9. HALPERT

FUTURE ROLES FOR LITHIUM RECHARGEABLE BATTERIES

PLANETARY MISSIONS
(Prime Power and RTG Augmentation)

GEOSYNCHRONOUS MISSIONS
(100 Cycles per Year)

MOBILE EQUIPMENT/VEHICLES
(Rover)

ASTRONAUT EQUIPMENT
(Tools, Backpack etc.)

FIGURE 10. HALPERT

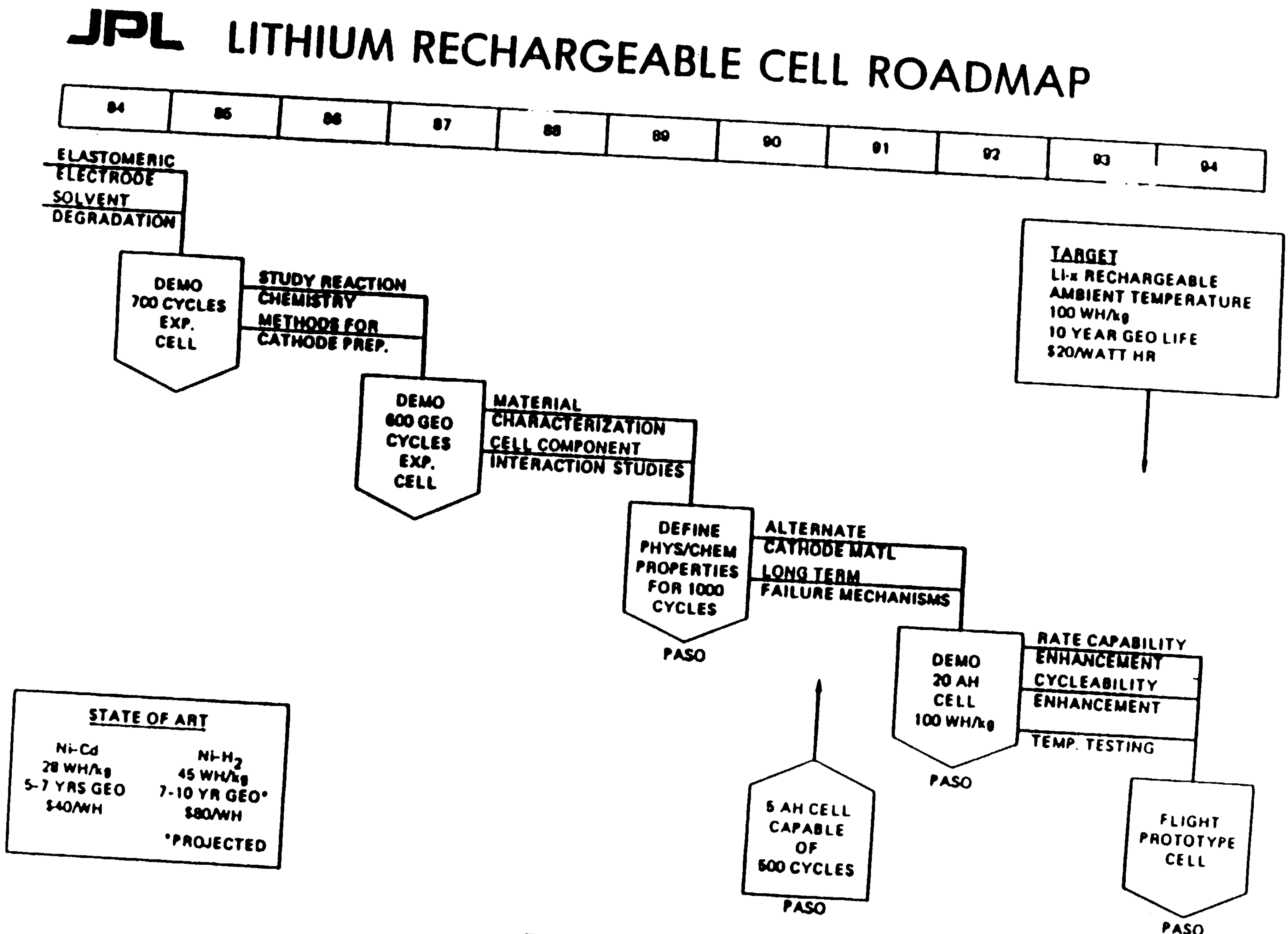


FIGURE 11. HALPERT

JPL

ADVANCED ELECTROCHEMICAL ENERGY STORAGE

TECHNOLOGY ISSUES AND DEVELOPMENTS FOR USE OF Li–TiS_2

ISSUES		DEVELOPMENTS
ELECTROLYTE DEGRADATION	⇨	NEW ELECTROLYTE DEMONSTRATED — JPL (EC — 2 MeTHF)
ENHANCED RATE CAPABILITY	⇨	THIN ELECTRODE DEMONSTRATED — GRACE CHEM (TO 5 MIL)
LITHIUM RECHARGEABILITY AND SAFETY	⇨	ELECTRODE MODS PREVENT LITHIUM POWDER FORMATION LI ALLOY — STANFORD LI POLYMER — CAN. NRC
CELL UNIFORMITY IN A BATTERY	⇨	OVERCHARGE CAPABILITY DEMONSTRATED USING POLYSULFIDES (TELAVIV UNIV)

- Li-TiS_2 FOR HIGH RATE, IMPROVED CYCLE LIFE 100 WH/kg, AMBIENT TEMPERATURE, VERY PROMISING
- IMMEDIATE NEED TO EVALUATE THESE IMPROVEMENTS IN MANUFACTURED CELLS

FIGURE 12. HALPERT

TECHNOLOGY GOALS

INCREASE RATE CAPABILITY
(Cell and Component Design)

MINIMIZE THERMAL EFFECTS
(Cell and Battery Design)

WITHSTAND ENVIRONMENTAL CONDITIONS
(Cell and Battery Design)

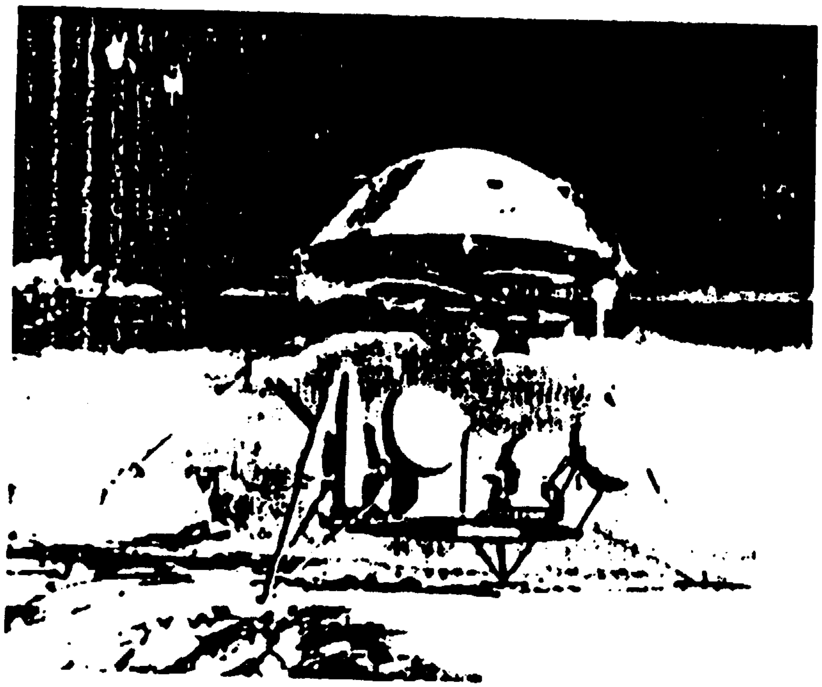
INCORPORATE SAFETY
(Chemistry, Component, and Cell Design)

BUILD IN HIGH RELIABILITY
(Manufacturing Control and Q.C).

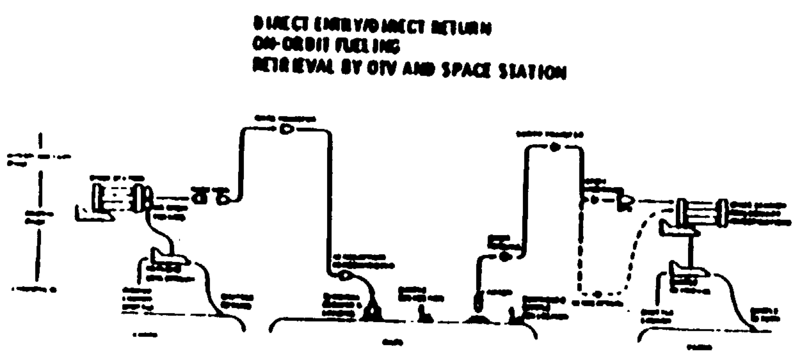
FIGURE 13. HALPERT

JPL

Planetary Technology
Mars Sample Return



Reference Mission Profile

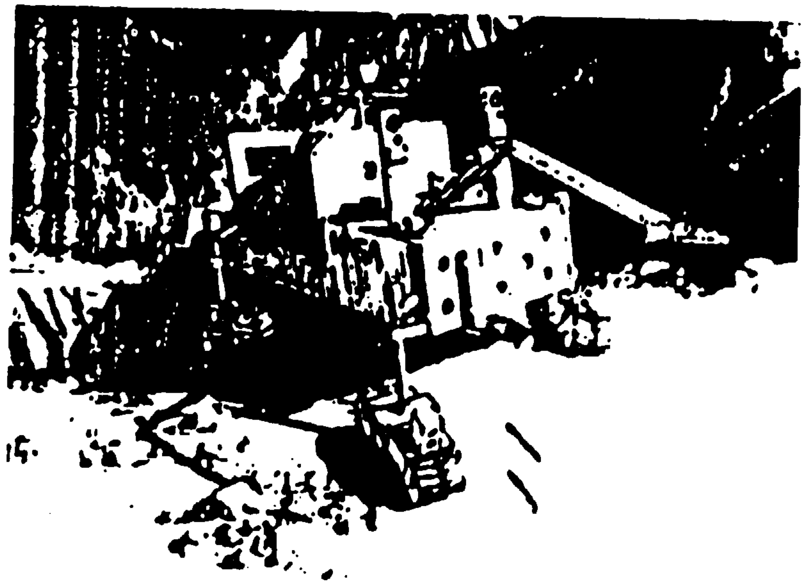


Technology Needs

- ROVER
  - AUTOMATION/AUTONOMY
  - ADVANCED COMPUTATIONAL CAPABILITY
  - IMPROVED POWER CONVERSION AND DISTRIBUTION (SEE MM II)
  - SAMPLE MAINTENANCE
- LANDER
  - AEROMANEUVERING/AEROCAPTURE
  - TERMINAL GUIDANCE
- ORBITER
  - AUTOMATED RENDEZVOUS AND DOCKING
- MARS ASCENT VEHICLE
  - SAMPLE CONTAINMENT
  - ASCENT PROPULSION - LO_2/HC, ISPP
- EARTH RETURN VEHICLE
  - AEROMANEUVERING
  - SAMPLE CONTAINMENT AND TRANSFER
- OVERALL
  - COST MINIMIZATION
  - AUTOMATION OF MISSION OPERATIONS
  - THERMAL CONTROL

Mars Sample Return

JPL Rover Key to Collection of Required Samples



Mission Capabilities

- OBTAIN SAMPLES WITHIN 100 km OF LANDING SITE AND RETURN THEM TO MARS ASCENT VEHICLE
- EXPLORATORY VEHICLE NORMALLY NEEDING ONE INTERACTION WITH EARTH PER DAY
  - HUMAN INTERVENTION 9-42 MINUTES AWAY IF NEEDED

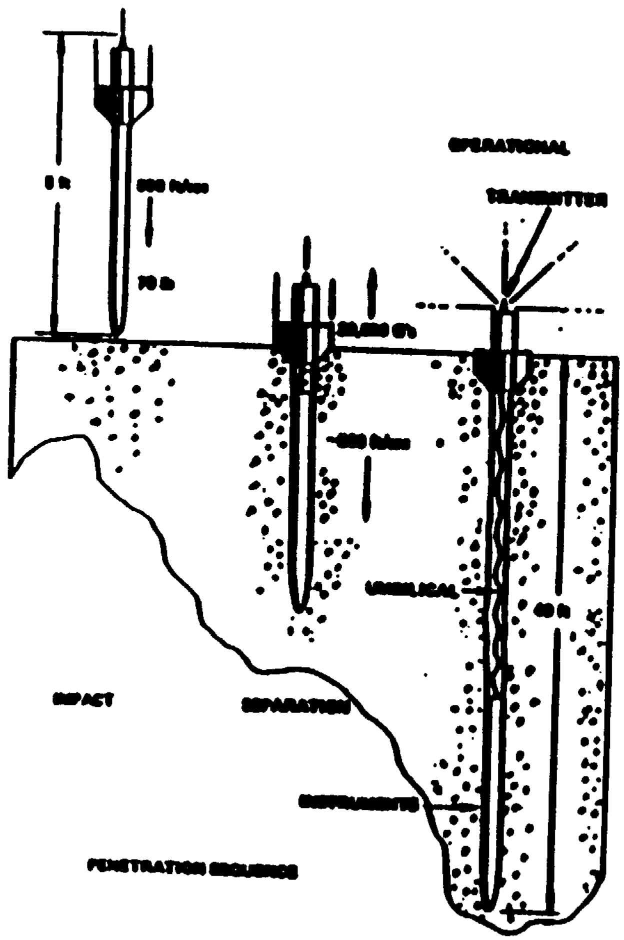
Rover Functions

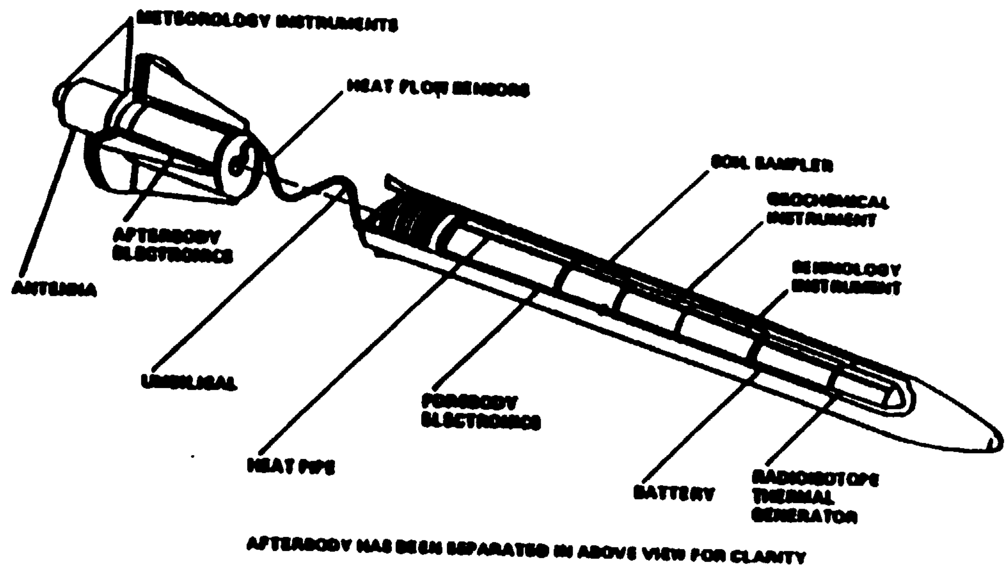
- NAVIGATE TO AND EXPLORE SAMPLE COLLECTION SITES
- OBTAIN SAMPLES OF INTEREST
- MAINTAIN SAMPLES IN PRISTINE STATE
- SELF-MAINTAINANCE: FAULT TOLERANCE, DIAGNOSIS, CORRECTION
- RETURN TO MARS ASCENT VEHICLE
- TRANSFER SAMPLES TO MARS ASCENT VEHICLE

FIGURE 15. HALPERT

DMANO Mission

JPL Penetrometer Design for Acceleration Environment Major Technology Need





Technology Needs

- ELECTRONIC DEVICE DESIGN METHODOLOGY
- INSTRUMENT DESIGN METHODOLOGY

FIGURE 16. HALPERT

CONCLUSIONS

SPACE NEEDS EXIST
(Lighter Weight, Smaller Volume, Long Storage Life)

LITHIUM PRIMARY AND SECONDARY BATTERIES BECOMING VIABLE
(Technology Improvements and Safety)

GREATER ENERGY STORAGE REQUIRED FOR FUTURE SPACE MISSIONS

LITHIUM PRIMARY BATTERIES IN USE

LITHIUM SECONDARIES WILL FOLLOW

FIGURE 17. HALPERT

"THE SELECTION OF SAFE BATTERIES FOR SARSAT 406 MHz BEACONS"

DAVID PERRONE presented by GERALD HALPERT

Gerald Halpert (JPL) gave the presentation "The Selection of Safe Batteries for SARSAT 406 MHz Beacons." This talk was originally scheduled to be given by David Perrone (JPL).

The Search and Rescue Satellite (SARSAT) is a joint venture among United States, Canada, France, and Soviet Union. Both marine and aeronautical vehicles as well as persons who carry Emergency Locator Transmitter (ELT) or Emergency Position Indicating Radio Beacon (EPIRB) will be able to send signals on emergency to the SARSAT satellite. The intercepted signal is then relayed to a Local User Terminal which then coordinates the rescue with Mission Control Center and the Rescue Coordination Center. Batteries which are safe and have long storage life are needed for the ELT and EPIRB.

The battery requirements for the digital logic is:

power	20mW
nominal voltage	12V
minimum voltage	7.5V
duty cycle	continuous
capacity	0.1Ah

The battery requirements for the homing beacon load is:

power	100mW
nominal voltage	12V
minimum voltage	7.5V
duty cycle	continuous
capacity	0.5Ah

Two classes of beacons were identified based on the operation temperature requirements. Class 1 beacons operate at -40 degrees to 55 degrees C; this is a long term development. A near term work concentrated on class 2 beacons which has an operating temperature requirement of -20 degrees to 55 degrees C. The storage life for both classes is for 2 to 5 years at -40 degrees to 71 degrees C. Safety was critical, for no hazard must be posed by the batteries to operating or non-operating ships, aircrafts, or their personnel.

The JPL work centered around identifying the candidate electrochemical systems for the SARSAT batteries. It then conducted limited testing of the candidate systems, followed by recommending a battery system as a near term alternative to the lithium-liquid cathode systems. It then recommended an approach to obtain an optimum battery system.

Various commercially available power sources were evaluated with a numerical rating system. The cell chemistries were rated on safety, operating temperature requirements, energy density, rate capability, and charge retention. The rating are summarized in Figures 8 and 9. From this evaluation, 5 candidate systems were chosen: 2/3A size $LiMnO_2$, 2/3A size $Li(CF)_n$, prismatic $LiAgV_2O_{5.5}$, C size CdHgO, and D size alkaline. The characteristics of these selected candidates are outlined in Figure 10.

To evaluate the 5 systems, Peronne and Attia examined the manufacturer's data. They also obtained voltage-pulse current profile to determine the maximum current capability for puse mode operation and to size the battery to beacon power demands. An experimental evaluation of the beacon simulation was done to evaluate cell performance using beacon duty cycle. Other areas tested included capacity loss test to ascertain cell shelf life under severe storage conditions, and abuse tests to investigate the most likely events associated with beacon application (short circuit, overdischarge, charge, recharge, etc.).

From these tests two safe, commercially available cells have emerged which can meet all requirements for the near term beacon application: 2/3A size $LiMnO_2$, and 2/3A size $Li(CF)_n$. Two other safe systems have potential for the long term beacon application, but they require further development: prismatic $LiAgV_2O_{5.5}$, and C size CdHgO. Alkaline cells cannot meet the SARSAT requirements for unattended storage and have marginal pulse capability at low temperatures.

Q. Broderick (GTE): What is the timeline for selecting the battery?

A. We recommended the carbon monofluoride and the manganese dioxide cell. The SARSAT people at GSFC will decide. They are concerned about safety on passenger aircraft. This is a DOT issue.

Q. Stearns (GE Astro Space): Lithium thiochloride is good. Do we want a ventless cell?

A. Nonvented cells are wanted in space. Vented cells would make the ordinary consumer nervous. Other countries do recommend them.

Q. _______: How many cycles are wanted?

A. These are primaries only. We want the beacon to survive for three to five years and have 48 to 96 hours of operations.

Q. Sulkes (USALABWM): Suppose the satellite acquires the beacon; does the beacon turn off?

A. The beacon can't be turned off until the next satellite pass

Q. Krehl (Electrochem): Is there an active program for the safety of the thionylchloride cell?

A. We're working on safety. Determining whether a system is truly safe is tough.

Q. Willis (AT&T): Could we cut down the pulse signal frequency to 10 Hz to save the batteries?

A. It sounds logical. There is a trend to adopting a 2 W beacon but the signal may be too weak. For now we adhere to 5 W.

Q. Maurer (AT&T): The system has a major problem -- 98 percent false alarms. Rescue crews have been injured pursuing false alarms.

THE SELECTION OF SAFE BATTERIES FOR SARSAT 406 MHz BEACONS

JPL

PREPARED FOR THE 1987
NASA/GSFC BATTERY WORKSHOP
NOVEMBER 4, 1987

ALAN ATTIA AND DAVE PERRONE
ELECTROCHEMICAL POWER GROUP
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

FIGURE 1. PERRONE

AGENDA

APPLICATION OVERVIEW

BATTERY REQUIREMENTS

SCOPE OF JPL ACTIVITY

BATTERY SELECTION ANALYSIS

CHARACTERISTICS OF SELECTED BATTERIES

EXPERIMENTAL EVALUATION

CONCLUSIONS OF JPL STUDY

FIGURE 2. PERRONE

JPL

APPLICATION OVERVIEW
BASIC OPERATING CONCEPT

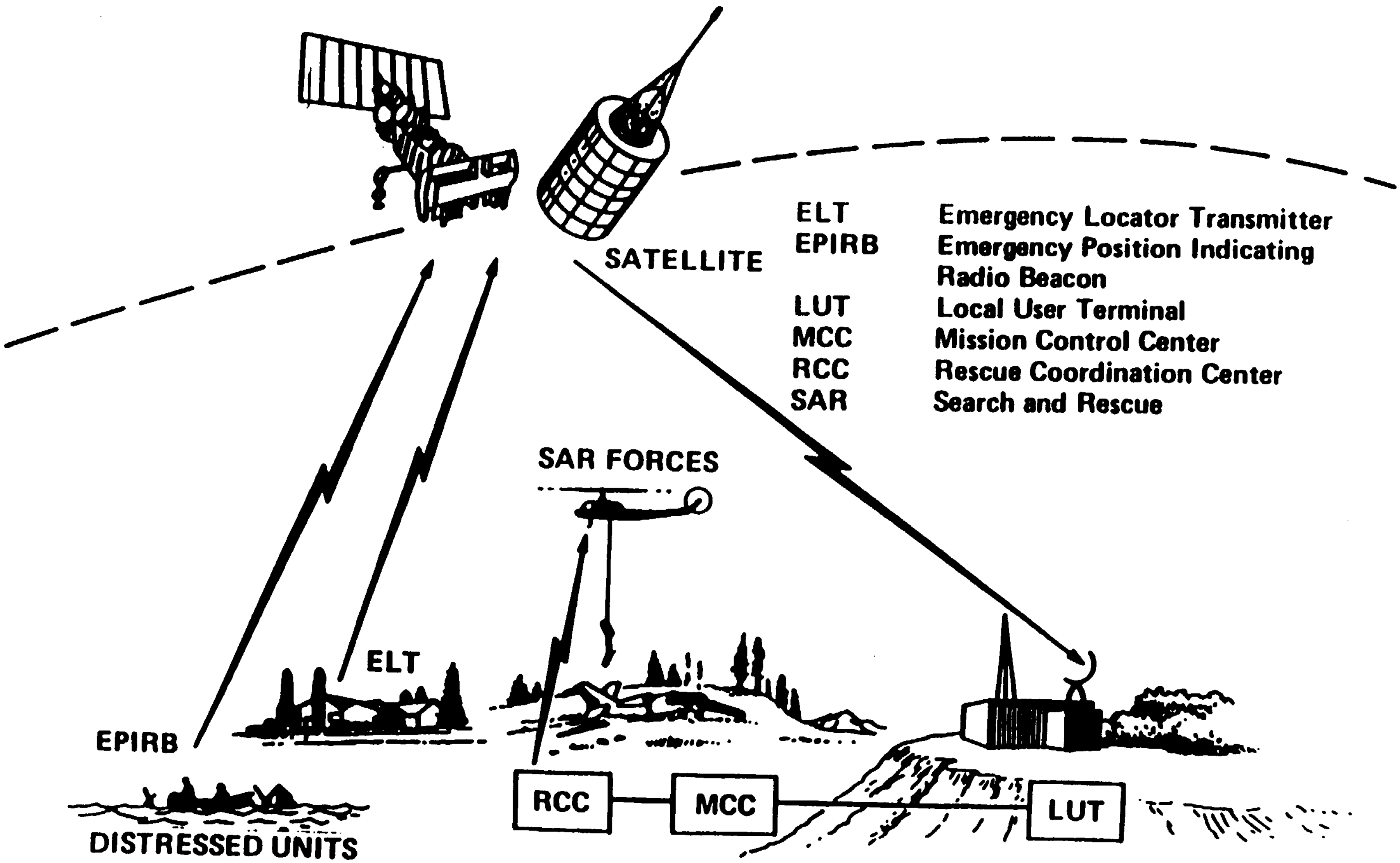


FIGURE 3. PERRONE

BATTERY REQUIREMENTS-BACKGROUND LOADS

- **DIGITAL LOGIC**

POWER	20 MW
NOMINAL VOLTAGE	12 VOLTS
MINIMUM VOLTAGE	7.5 VOLTS
DUTY CYCLE	CONTINUOUS
CAPACITY	0.1 AH

- **HOMING BEACON LOAD**

POWER	100 MW
NOMINAL VOLTAGE	12 VOLTS
MINIMUM VOLTAGE	7.5 VOLTS
DUTY CYCLE	CONTINUOUS
CAPACITY	0.5 AH

FIGURE 4. PERRONE

C-2

BATTERY REQUIREMENTS - MISC

- **OPERATING TEMPERATURE**
  - -40 TO 55 C (CLASS 1 BEACONS)
  - -20 TO 55 C (CLASS 2 BEACONS)
- **STORAGE TEMPERATURE**
  - -40 TO 71 C
- **TEMPERATURE VARIATION**
  - UNCONTROLLED OUTDOOR ENVIRONMENT
- **STORAGE LIFE**
  - 2 TO 5 YEARS
- **MECHANICAL**
  - VIBRATION FROM AIRCRAFT OR SHIP
- **SAFETY**
  - NO HAZARD TO OPERATING OR NON-OPERATING SHIPS OR AIRCRAFT OR THEIR PERSONNEL

FIGURE 5. PERRONE

SCOPE OF JPL ACTIVITY

- IDENTIFY CANDIDATE ELECTROCHEMICAL SYSTEMS
- CONDUCT LIMITED TESTING
- RECOMMEND A BATTERY SYSTEM AS A NEAR TERM ALTERNATIVE TO THE LITHIUM - LIQUID CATHODE SYSTEMS
- RECOMMEND AN APPROACH TO OBTAIN AN OPTIMUM BATTERY SYSTEM

FIGURE 6. PERRONE

QUANTITATIVE BASIS FOR IDENTIFICATION OF CANDIDATE ELECTROCHEMICAL SYSTEMS

- **SAFETY**

1 LITHIUM - LIQUID CATHODE
2 LITHIUM - SOLID CATHODE
3 AQUEOUS

- **TEMP. CAPABILITY**

1 OPERATES ABOVE −20C
2 OPERATES DOWN TO −20C
3 OPERATES DOWN TO −40C

- **ENERGY DENSITY**

1 < 100 WH/L
2 101 - 299 WH/L
3 > 300 WH/L

- **RATE CAPABILITY**

1 CAN'T MEET REQUIREMENTS
2 POWERS DC LOAD ONLY
3 POWERS PULSE & DC LOADS

- **CHARGE RETENTION**

1 < 50% AFTER 1 YR AT 50C
2 > 50% AFTER 1 YR AT 50C
3 > 50% AFTER 1 YR AT 60C

FIGURE 7. PERRONE

RATINGS OF COMMERCIALLY AVAILABLE POWER SOURCES

SYSTEM	SAFETY	ENERGY DENSITY	CHARGE RETENT	HIGH RATE	LOW TEMP	TOTAL
Li-SO_2	1	3	3	3	3	13
Li-$SOCl_2$	1	3	3	3	3	13
Li-SO_2Cl_2	1	3	2	3	3	12
Li-BCX	1	3	3	3	3	13
Li-MnO_2	2	3	3	3	2	13
Li-CuO	2	3	3	2	2	12
Li-$AgV_2O_{5.5}$	2	3	3	3	3	14
Li-Ag_2CrO_4	2	3	3	1	1	10
Li-$(CF)_n$	2	3	3	3	2	13
Li-TiS_2	2	2	2	3	2	11
Li-MoS_2	2	2	2	3	2	11
Li-FeS_2	2	3	2	1	2	10

FIGURE 8. PERRONE

RATINGS OF COMMERCIALLY AVAILABLE POWER SOURCES

SYSTEM	SAFETY	ENERGY DENSITY	CHARGE RETENT	HIGH RATE	LOW TEMP	TOTAL
$Mg-MnO_2$	3	2	3	3	2	13
$Zn-MnO_2$	3	2	1	3	2	11
$Zn-AgO$	3	2	1	3	2	11
$Zn-O_2$	3	3	1	2	1	10
$Zn-NiOOH$	3	2	1	3	2	11
$Zn-HgO$	3	3	2	3	1	12
$H_2-NiOOH$	3	1	1	3	2	10
$Cd-HgO$	3	3	3	3	3	15
$Cd-NiOOH$	3	1	1	3	2	10
$Cd-AgO$	3	2	1	3	3	12
$Pb-PbO_2$	3	1	1	3	3	11

Figure 9. Perrone

CHARACTERISTICS OF SELECTED BATTERY CANDIDATES

	Li-Mn02	Li-(CF)n	Li-AgVO	Cd-HgO	ALKALINE
CELL TYPE	2/3A	2/3A	PRISMATIC	C	D
CELL NUMBER	12 3 X 4	12 3 X 4	5 1 STRING	14 1 STRING	8 1 STRING
BATTERY WEIGHT	210 g	210 g	350 g	1.8 Kg	1.0 Kg
BATTERY VOLUME	88 cc	88 cc	123 cc	540 cc	523 cc
TEMP RANGE	-20 TO 55 C	-20 TO 55 C	-40 TO 55 C	-40 TO 85 C	-10 TO 55 C
SHELF LIFE	>2 YRS	>2 YRS	5 YRS	>5 YRS	<1 YR
COST $	35-50	35-50	200	200	20

FIGURE 10. PERRONE

EXPERIMENTAL EVALUATION

- MANUFACTURERS DATA
- VOLTAGE-PULSE CURRENT PROFILE
- BEACON SIMULATION
- CAPACITY LOSS
- ABUSE TESTS

FIGURE 11. PERRONE

EXPERIMENTAL EVALUATION
VOLTAGE-PULSE CURRENT PROFILE

OBJECTIVE

- TO DETERMINE MAXIMUM CURRENT CAPABILITY FOR PULSE MODE OPERATION
- TO SIZE BATTERY TO BEACON POWER DEMANDS

APPROACH

- APPLY 10 MA CONSTANT CURRENT LOAD
- SUPERIMPOSE HIGH CURRENT PULSE FOR 620 MS AT 50 SECOND INTERVALS
- CHANGE PULSE CURRENT WHEN CELL VOLTAGE STABILIZES

FIGURE 12. PERRONE

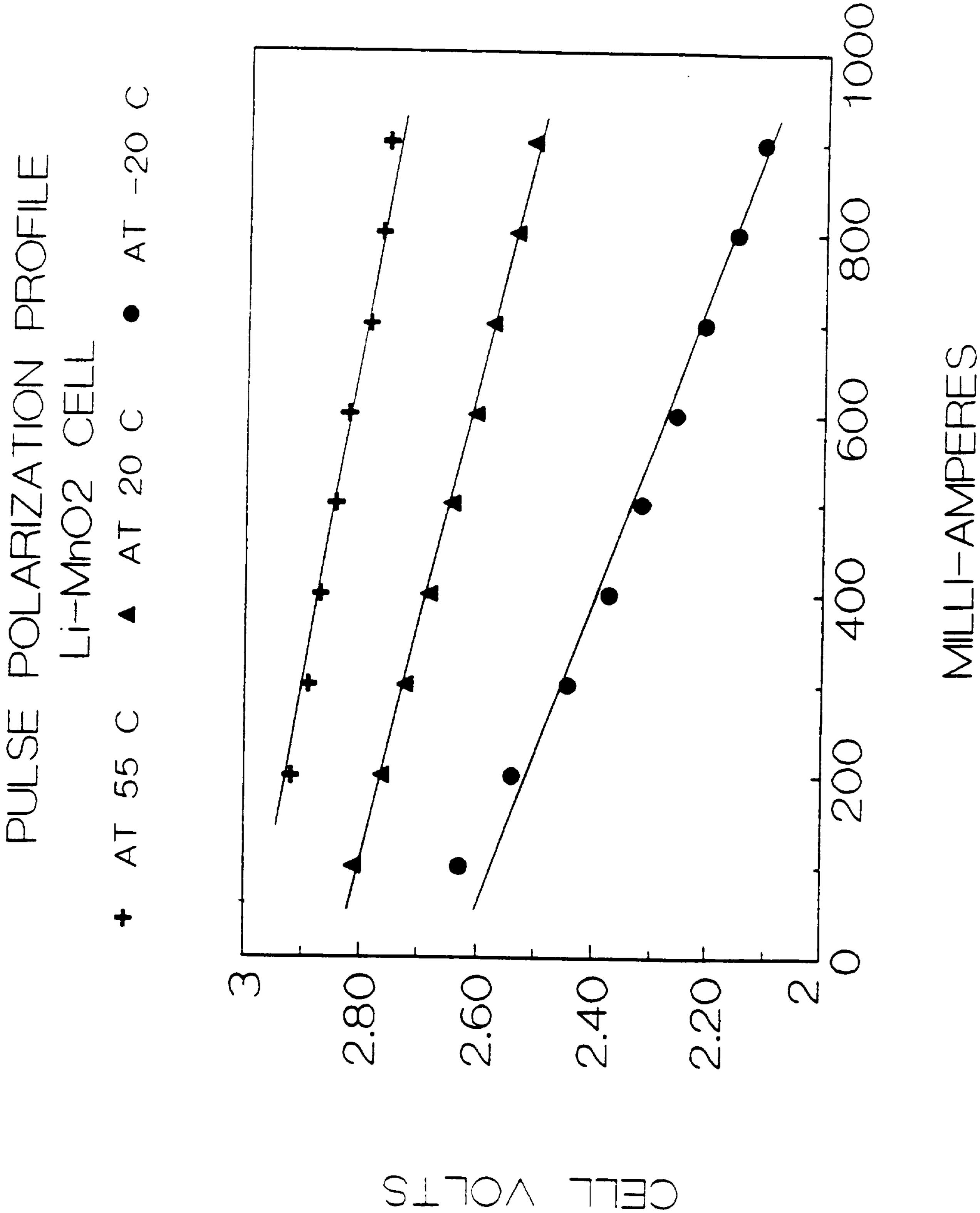


FIGURE 13. PERRONE

EXPERIMENTAL EVALUATION
POLARIZATION DATA

CELL TYPE	TEMPERATURE DEGREES C	MIN VOLTAGE FUNCTION
Li-MnO_2 2/3A	+20	2.28 - 0.41P
	-20	2.58 - 0.53P
Li-$(CF)_n$ 2/3A	+20	2.28 - 0.41P
	-20	1.99 - 0.60P
Li-$(CF)_n$ "C"	-30	1.95 - 0.38P
ALKALINE "D"	+20	1.52 - 0.12P
	-20	1.47 - 0.36P
ALKALINE 9V	+20	8.96 - 1.12P
	-20	9.22 - 4.60P
Cd-HgO 3AH	+20	0.74 - 0.28P
	-20	0.82 - 1.21P
	-30	0.84 - 1.65P
	-40	0.62 - 4.30P
Li-$AgV_2O_{5.5}$	+20	3.07 - 0.21P
	-20	2.77 - 0.47P
	-30	2.69 - 0.77P

FIGURE 14. PERRONE

EXPERIMENTAL EVALUATION
BEACON SIMULATION

OBJECTIVE

- TO EVALUATE CELL PERFORMANCE USING BEACON DUTY CYCLE

APPROACH

- APPLY 10 MA CONSTANT CURRENT LOAD
- SUPERIMPOSE HIGH CURRENT PULSE FOR 620 MS AT 50 SECOND INTERVALS

FAILURE CRITERIA

- 1/2 OF INITIAL POWER OUTPUT
- KNEE OF CELL DISCHARGE CURVE
- ELAPSED TIME >= 50 HOURS

FIGURE 15. PERRONE

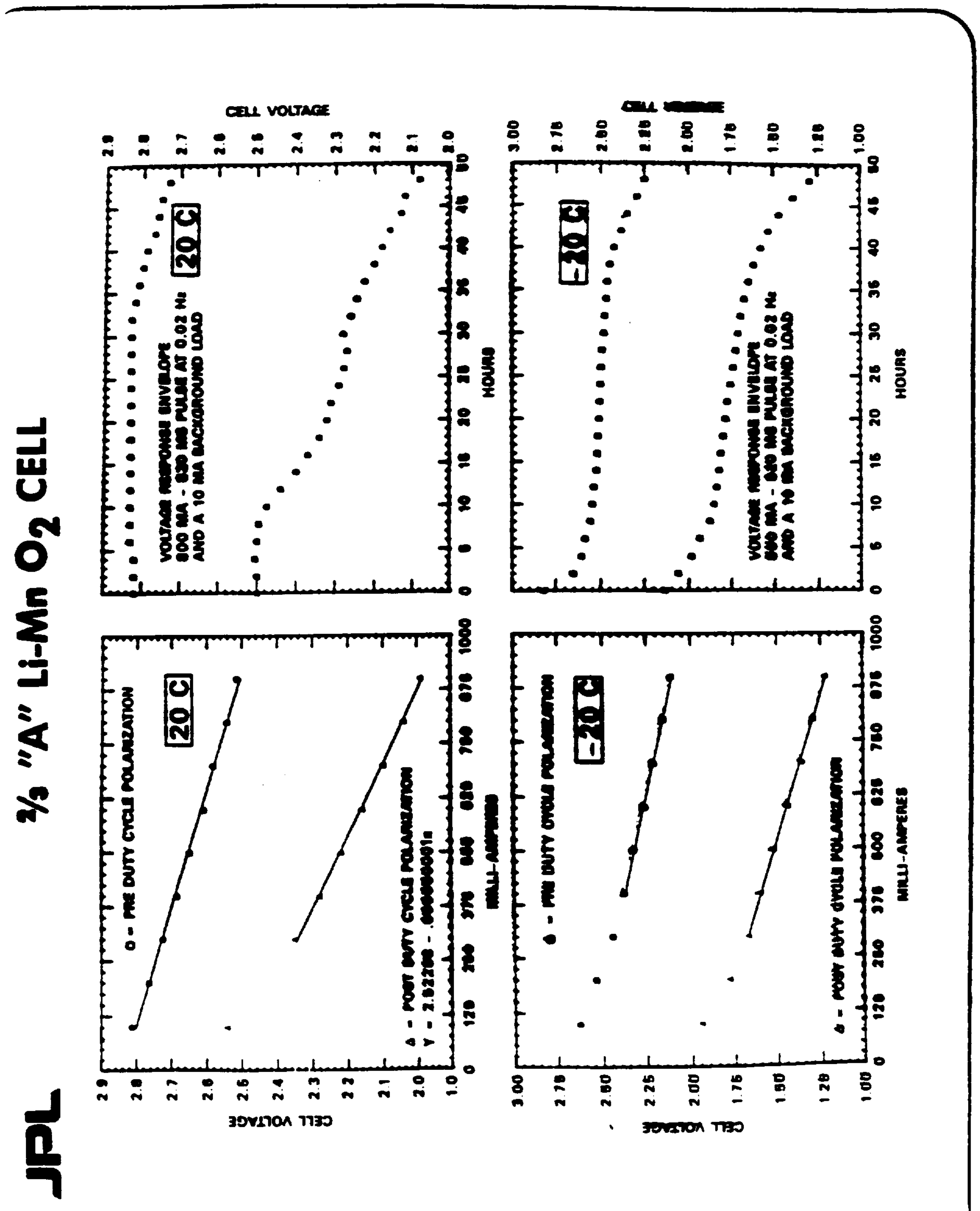


FIGURE 16. PERRONE

EXPERIMENTAL EVALUATION
BEACON SIMULATION

CELL TYPE	TEMPERATURE DEGREES C	PULSE AMPLITUDE	HOURS TO FAILURE
Li-MnO_2 2/3A	+20	0.80 A	>50
	-20	0.80 A	48
Li-$(CF)_n$ 2/3A	+20	0.80 A	50
Li-$(CF)_n$ "C"	-30	2.00 A	42
ALKALINE "D"	+20	2.00 A	>50
	-20	2.00 A	22
ALKALINE 9V	+20	0.20 A	>50
	-20	0.20 A	18
Cd-HgO 3AH	+20	0.15 A	>50
	-20	0.15 A	>50
	-30	0.15 A	>50
	-40	0.08 A	>50
Li-$AgV_2O_{5.5}$	-30	2.00 A	30
	-40	1.50 A	44

FIGURE 17. PERRONE

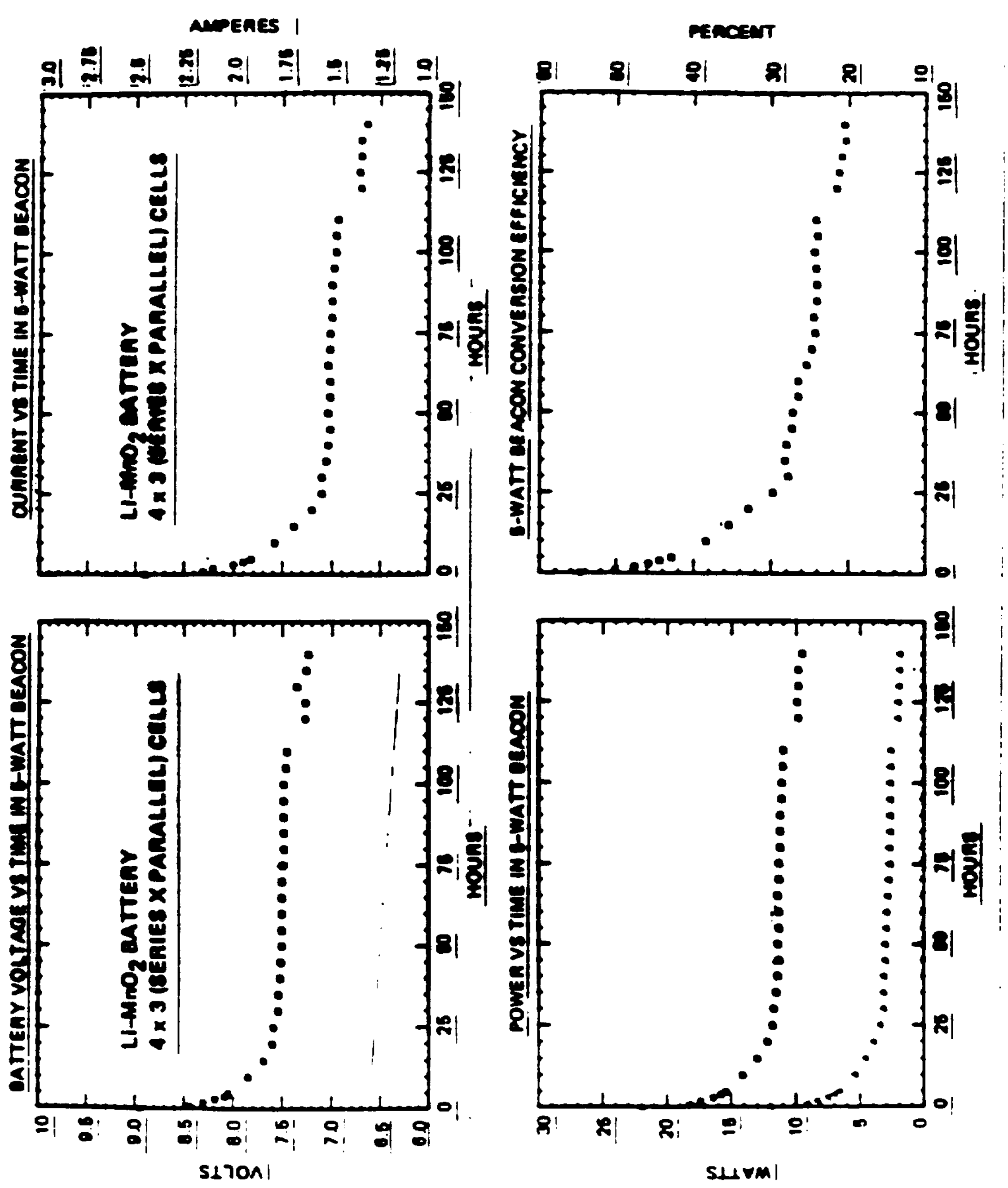


FIGURE 18. PERRONE

EXPERIMENTAL EVALUATION CAPACITY LOSS

OBJECTIVE

- TO ASCERTAIN CELL SHELF LIFE UNDER SEVERE STORAGE CONDITIONS

APPROACH

- DETERMINE INITIAL C/50 CAPACITY AT 25C
- 60 DAY STORAGE OF FRESH CELL AT 55C
- DETERMINE C/50 CAPACITY AT 25C

FIGURE 19. PERRONE

EXPERIMENTAL EVALUATION

CAPACITY LOSS(1)

CELL TYPE	<-- PERCENT LOSS --> JPL DATA	MFG DATA
Li-MnO_2	1	2
Li-$(CF)_n$	7	1-2
ALKALINE "D"	67	12
ALKALINE "9V"	13	12
Cd-HgO	4	1-2
Li-$AgV_2O_{5.5}$	N/A	0

(1) AFTER 60 DAYS AT 55C

FIGURE 20. PERRONE

EXPERIMENTAL EVALUATION
ABUSE TESTS

OBJECTIVE

- INVESTIGATE THE MOST LIKELY EVENTS ASSOCIATED WITH BEACON APPLICATION

APPROACH

- SHORT CIRCUIT - 5 MOHM LOAD
- OVERDISCHARGING - TO 30% OF C20
- CHARGING - TO 30% OF C20 AT C/20
- RECHARGING - 70% DOD AT C/20
  THEN 125% CHARGE AT C/20

FIGURE 21. PERRONE

EXPERIMENTAL EVALUATION
ABUSE TESTING

	$Li-MnO_2$	$Li-(CF)_n$
SHORT CIRCUIT 5 MOHM	NO VENT 55F	NO VENT 73F
OVERDISCHARGE 30% AT C/20	NO VENT 6F	NO VENT 3F
CHARGE 30% AT C/20	NO VENT 8F	SOFT VENT 18F
RECHARGE TO 70% OF C20 125% AT C/20	NO VENT 4F	NO VENT 3F

FIGURE 22 PERRONE

RESULTS OF JPL STUDY

- TWO SAFE, COMMERCIALLY AVAILABLE, BATTERIES CAN MEET ALL REQUIREMENTS FOR THE NEAR TERM BEACON APPLICATION

  LITHIUM-MANGANESE DIOXIDE
  LITHIUM-CARBON MONOFLUORIDE

- TWO OTHER SAFE SYSTEMS HAVE POTENTIAL FOR THE LONG TERM BEACON APPLICATION, BUT REQUIRE FURTHER DEVELOPMENT

  CADMIUM-MERCURIC OXIDE
  LITHIUM-SILVER VANADIUM PENTOXIDE

- ALKALINE BATTERIES CAN NOT MEET THE SARSAT REQUIREMENTS FOR UNATTENDED STORAGE AND HAVE MARGINAL PULSE CAPABILITY AT LOW TEMPERATURES

FIGURE 23. PERRONE

"SOLID - SOLID PHASE CHANGE MATERIAL FOR THERMAL MANAGEMENT OF LITHIUM BATTERY PACKS"

ERIC DARCY

Eric Darcy (JSC) spoke on "Solid - Solid Phase Change Material for Thermal Management of Lithium Battery Packs." Thermal management is the main problem for lithium battery packs. Lithium thionyl chloride is the highest energy density system that has flown but it has a problem with inherent heat generation (Darcy [Figure 3]). The goal, then, is to find a material suitable for space flight which will provide effective heat sink mass and be safe. Solid-solid phase-change materials that were looked at were stycast and polyalcohols (Darcy [Figure 5]). Stycast is an epoxy casting resin that is commercially available. Polyalcohols are low-density derivatives of neopentane. Neopentyl glycol (NPG) forms polyalcohol. It has the solid-solid phase-change property and has the advantage of latent heat of transformation in going from phase 1 to phase 2 (Darcy [Figure 6]). Solid phase-change materials (PCM) have the advantage over liquids of not posing a containment problem (Darcy [Figure 7].) The specific heat of NPG is being studied now.

JSC is now trying to determine the specific heat and the sublimation rate of NPG and also its performance in a lithium cell. There is a program to correlate simple experimental results with theory, and then to apply the theory to larger battery packs (Darcy [Figure 8]).

Evaluation is to be completed by November 1987 and there will be further work to improve on poor conductivity and a high sublimation rate.

Q. Koenig (Chloride Silent Power): Was the weight disadvantage considered?

A. For vacuum conditions we need to provide a heat sink mass. We have compared stycast and polyalcohols and other materials such as aluminum. We consider NPG to be a lightweight material.

Q. Waggoner (Catalyst Research): How reversable is that paging??? over a period time?

A. This material has gone through a considerable number of cycles but it is intended for a primary battery.

Q. ______?: What about flammability properties?

A. Our materials laboratory has tested it. It's full compatible with materials that have been used on the Shuttle; it is non-toxic; and can be used for consumer applications.

Q. Kardarpa (General Dynamics): What about volume change with phase change?

A. It's minimal. I couldn't detect it.

Q. Smith (Altus Corp.): How available is NPG?

A. It's relatively inexpensive. It has been used before in solar dynamics applications in liquid form.

Q. George (MSFC): What is the thermal conductivity?

A. 0.1 W/m-degree C. This needs to be improved.

Q. George (MSFC): What is the reactivity of NPG with lithium?

A. This will be studied later.

Q. Youngblood (GE Americom): Have you considered using a heat pipe to improve the thermal conductivity?

A. This has been considered.

NASA-S-87-02550

Johnson Space Center - Houston, Texas

1987 NASA/GSFC BATTERY WORKSHOP	PROPULSION & POWER DIV.	
	E.C. DARCY	11/4/87

THERMALLY MANAGING A LITHIUM BATTERY PACK WITH A SOLID-SOLID PHASE CHANGE MATERIAL

FIGURE 1. DARCY

NASA-S-87-02551

Johnson Space Center - Houston, Texas

SOLID-SOLID PHASE CHANGE MATERIAL	PROPULSION & POWER DIV.	
	E.C. DARCY	11/4/87

OUTLINE

- Li BATTERY PROBLEM
- THERMAL MANAGEMENT GOALS
- CANDIDATE POTTING MATERIALS
- NEOPENTYL GLYCOL
- EXPERIMENTAL
- STATUS

FIGURE 2. DARCY

NASA-S-87-02552

Johnson Space Center - Houston, Texas

SOLID-SOLID PHASE CHANGE MATERIAL	**PROPULSION & POWER DIV.**	
	E.C. DARCY	**11/4/87**

Li/$SOCl_2$ — HIGHEST ENERGY DENSITY CHEMISTRY FLOWN

PROBLEM — INHERENT HEAT GENERATION DURING DISCHARGE MUST BE ACCOMMODATED TO MAINTAIN CELLS IN A SPACE BATTERY PACK WITHIN SAFE OPERATING TEMPERATURES

FIGURE 3. DARCY

NASA-S-87-02553

Johnson Space Center - Houston, Texas

SOLID-SOLID PHASE CHANGE MATERIAL	**PROPULSION & POWER DIV.**	
	E.C. DARCY	**11/4/87**

GOAL — **FIND A MATERIAL SUITABLE FOR SPACE FLIGHT WHICH WILL PROVIDE HEAT SINK MASS FOR A LITHIUM BATTERY PACK**

APPLICATIONS — **EMU AND MMU BATTERIES**
MODULAR BATTERY PACK (SS, CERV, MRSR)

FIGURE 4. DARCY

NASA-S-87-02555 | Johnson Space Center - Houston, Texas

SOLID-SOLID PHASE CHANGE MATERIAL	**PROPULSION & POWER DIV.**	
	E.C. DARCY	**11/4/87**

STYCAST — EPOXY CASTING RESINS

- RIGID AND SOLID
- THERMAL CONDUCTIVITY

POLYALCOHOLS DERIVATIVES OF NEOPENTANE

- CRYSTALLINE
- LOW DENSITY
- SOLID-SOLID PHASE CHANGE PROPERTY
  - TRANSITION TEMPERATURE RANGE (-31 TO 189 °C)
  - LATENT HEAT OF TRANSFORMATION (53 TO 303 kJ/kg)

FIGURE 5. DARCY

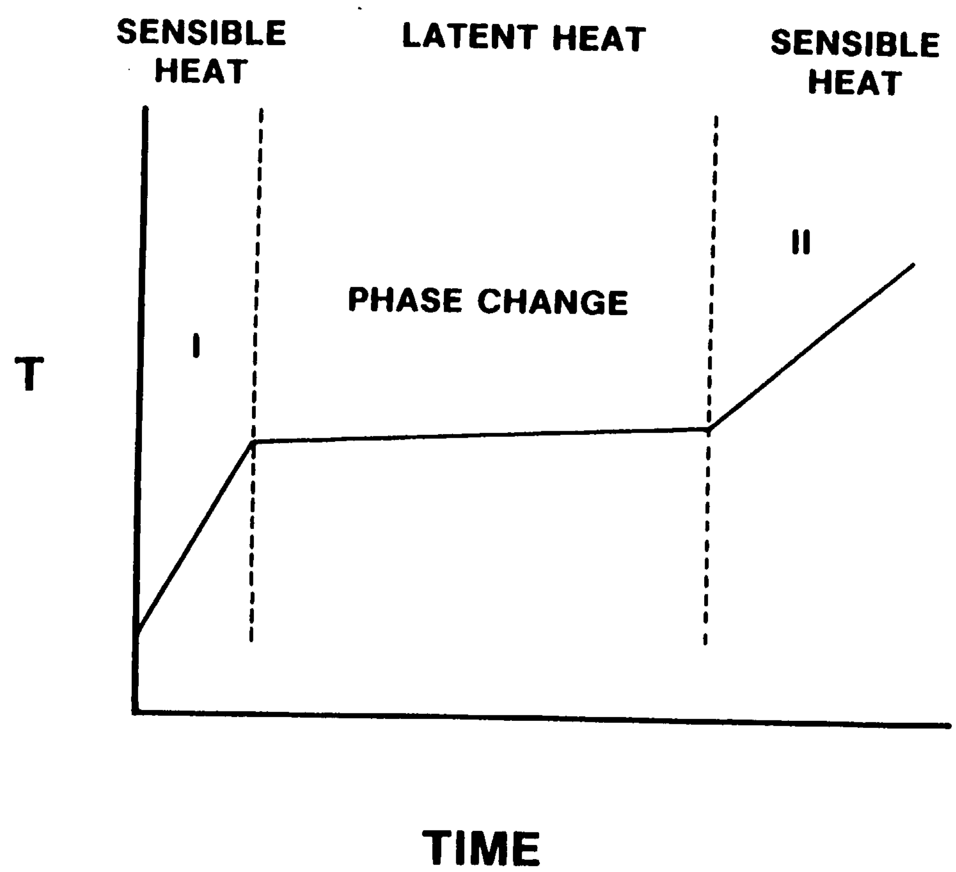
NASA-S-87-02557

Johnson Space Center - Houston, Texas

SOLID-SOLID PHASE CHANGE MATERIALS

PROPULSION & POWER DIV.

E.C. DARCY | 11/4/87



NPG

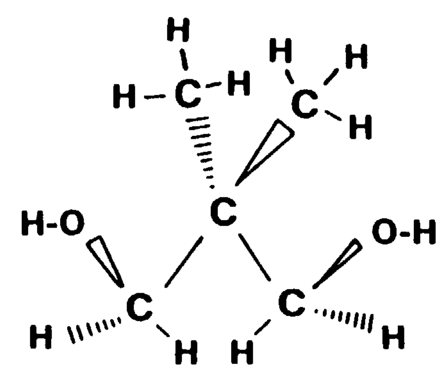


FIGURE 6. DARCY

NASA-S-87-02556

Johnson Space Center - Houston, Texas

SOLID-SOLID PHASE CHANGE MATERIAL	PROPULSION & POWER DIV.	
	E.C. DARCY	11/4/87

SOLID-SOLID PCM VS LIQUID-LIQUID PCM

- CONTAINMENT
- CYCLIC DEGRADATION
- SUPER-COOLING

NEOPENTYL GLYCOL (NPG)	$C_5H_{10}(OH)_2$
● TRANSITION TEMPERATURE	42 °C
● LATENT HEAT OF TRANSFORMATION	131 kJ/kg
● THERMAL CONDUCTIVITY	0.1 W/m °C
● SPECIFIC GRAVITY	1.0
● SPECIFIC HEAT	?

FIGURE 7. DARCY

NASA-S-87-02558 | Johnson Space Center - Houston, Texas

SOLID-SOLID PHASE CHANGE MATERIAL	**PROPULSION & POWER DIV.**	
	E.C. DARCY	**11/4/87**

JSC EVALUATION TASK

EXPERIMENTAL OBJECTIVES

- DETERMINATION OF SPECIFIC HEAT
- DETERMINATION OF SUBLIMATION RATE
- PERFORMANCE WITH Li CELL

THEORETICAL OBJECTIVES

- VALIDATE NUMERICAL MODEL WITH EXPERIMENTAL RESULTS
- PREDICT THERMAL BEHAVIOR OF VARIOUS BATTERY CONFIGURATIONS

FIGURE 8. DARCY

NASA-S-87-02559

Johnson Space Center - Houston, Texas

SOLID-SOLID PHASE CHANGE MATERIAL	PROPULSION & POWER DIV.	
	E.C. DARCY	11/4/87

STATUS AND FURTHER WORK

- COMPLETE EVALUATION BY NOV 1987
- IMPROVE ON NPG'S DISADVANTAGES
  - CONDUCTIVITY
  - SUBLIMATION

FIGURE 9. DARCY

"THERMAL PROPERTIES AND EFFECTS FOR LI/BCX CELLS"

WILLIAM CLARK

William Clark (Wilson Greatbatch Limited) spoke on "Thermal Properties and Effects for Li/BCX Cells."

This is a two-part study funded by JSC. BCX has undergone extensive study for space applications. Storage at 149 degrees C, for fifteen minutes, is a new requirement for D cells.

A test program was run in which 40 standard D cells were built. Thirty of these were run up to 149 degrees C for fifteen minutes and then cooled to room temperature. Twenty of the thirty cells that had been heated developed leaks.

Changes in cell height indicated that there was insufficient void volume in the cells (Clark [Figure 3]).

Redesigns included: reducing the thickness of the anode and the cathode; increasing the thickness of the header; and shortening the wound cell stack. All the redesigns were tried, and they passed the 149 degrees C storage test (Clark [Figure 5]). The discharge curves were excellent following the redesign. (Clark [Figure 6]).

An experimental determination showed that the heat capacities of BCX 72 D size batteries were independent of the state of discharge (Clark [Figure 11]).

During adiabatic discharges, cells were subjected to various loads and there were differences between running voltages and OCVs (Clark [Figure 13]). Also there was a roughly linear relation between temperature rise and heat evolved leading to a heat capacity of 0.28 cal/ g deg (Clark [Figure 14 and 15).

Q. Bis (Advanced Power Sources): Were there any safety tests performed after the 149 degrees C heating?

A. No

Q. Margalite (Tracor): Did you detect any additional parasitic chemical reactions? We would have needed a microcalorimetric.

A. No, we were not set up to do this.

Q. Stannick (HAC): Was the heat capacity just that of $LiTiCl_2$?

A. We looked at heat capacities due to all the components. We could get close to 0.24 cal/g deg. These might be fortuitous inputs.

THERMAL PROPERTIES AND EFFECTS FOR LI/BCX CELLS

- E. S. Takeuchi, C. F. Holmes and W. D. K. Clark
- Electrochem Industries Division
- Wilson Greatbatch Ltd.
- Clarence, New York 14031

FIGURE 1. W. CLARK

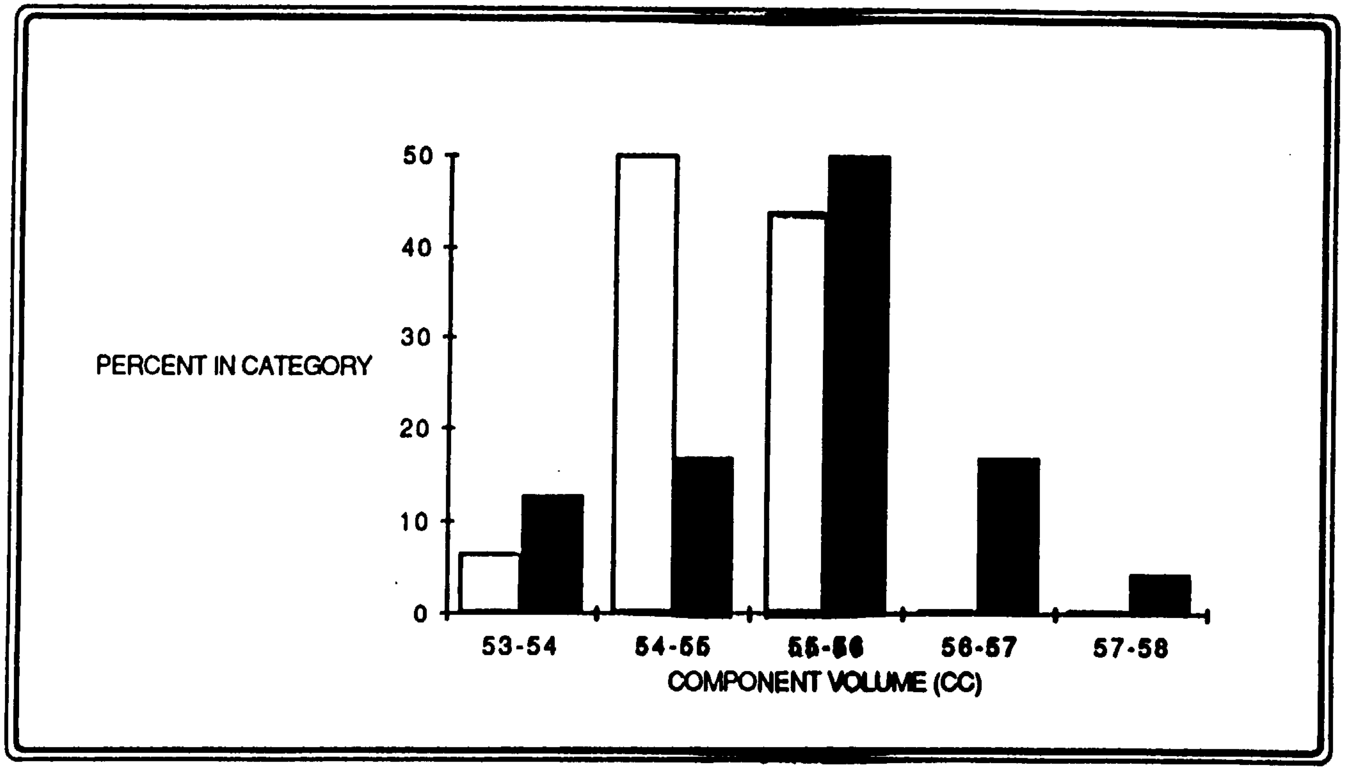


FIGURE 2. W. CLARK

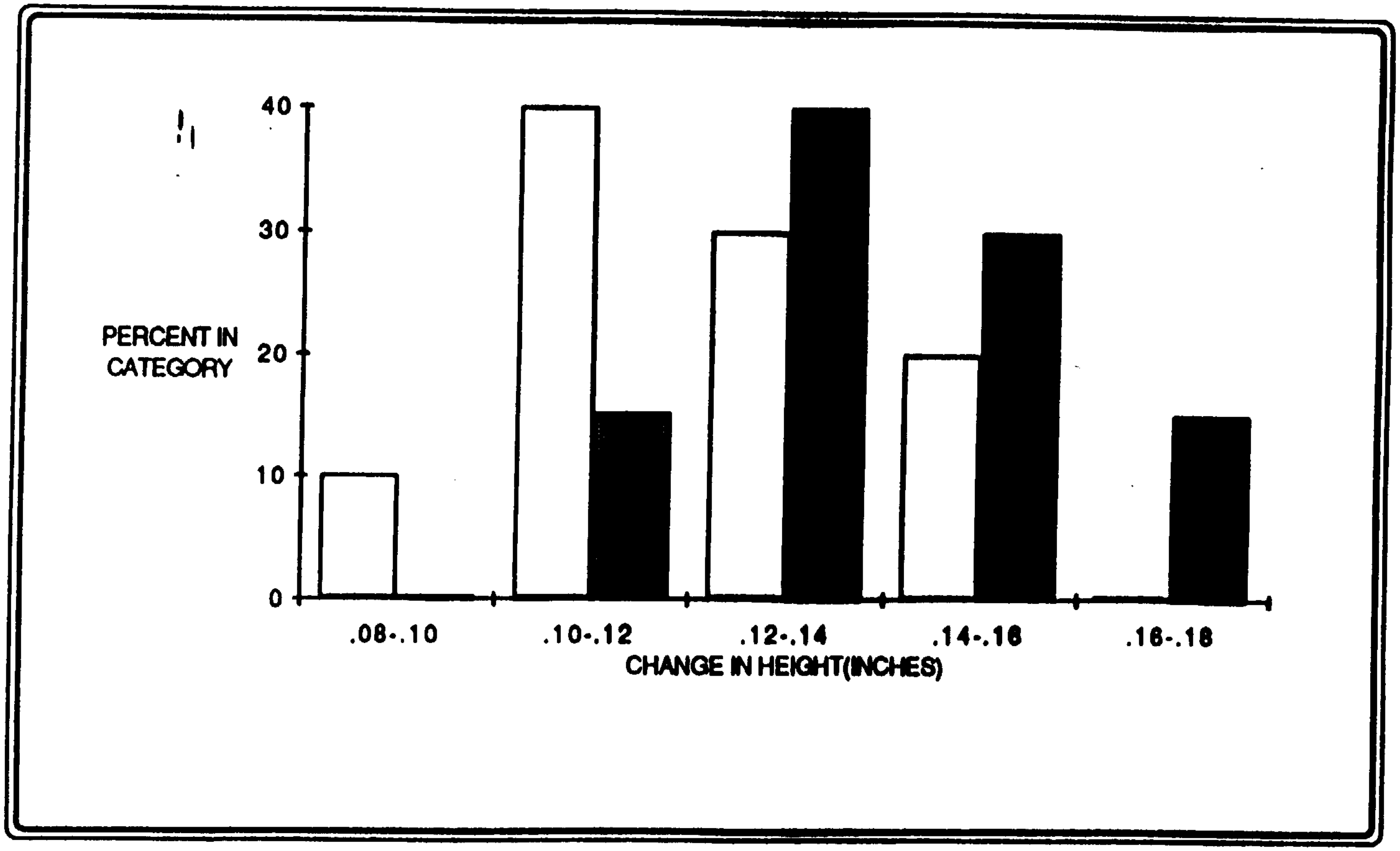


FIGURE 3. W. CLARK

List of the Redesigns

- Reduce thickness of anode and cathode
- Increase thickness of header
- Shorten wound cell stack

FIGURE 4. W. CLARK

Results of Temperature Exposure Tests for Redesign III Cells

Cell #	State	Height Change (inches)	Result
23859	BOL	-.005	Passed
23860	BOL	-.003	Passed
23861	BOL	0	Passed
23862	BOL	-.006	Passed
23863	BOL	.003	Passed
23864	BOL	-.002	Passed
23865	BOL	-.001	Passed
23866	BOL	-.002	Passed
23867	BOL	0	Passed
23868	BOL	.005	Passed

FIGURE 5. W. CLARK

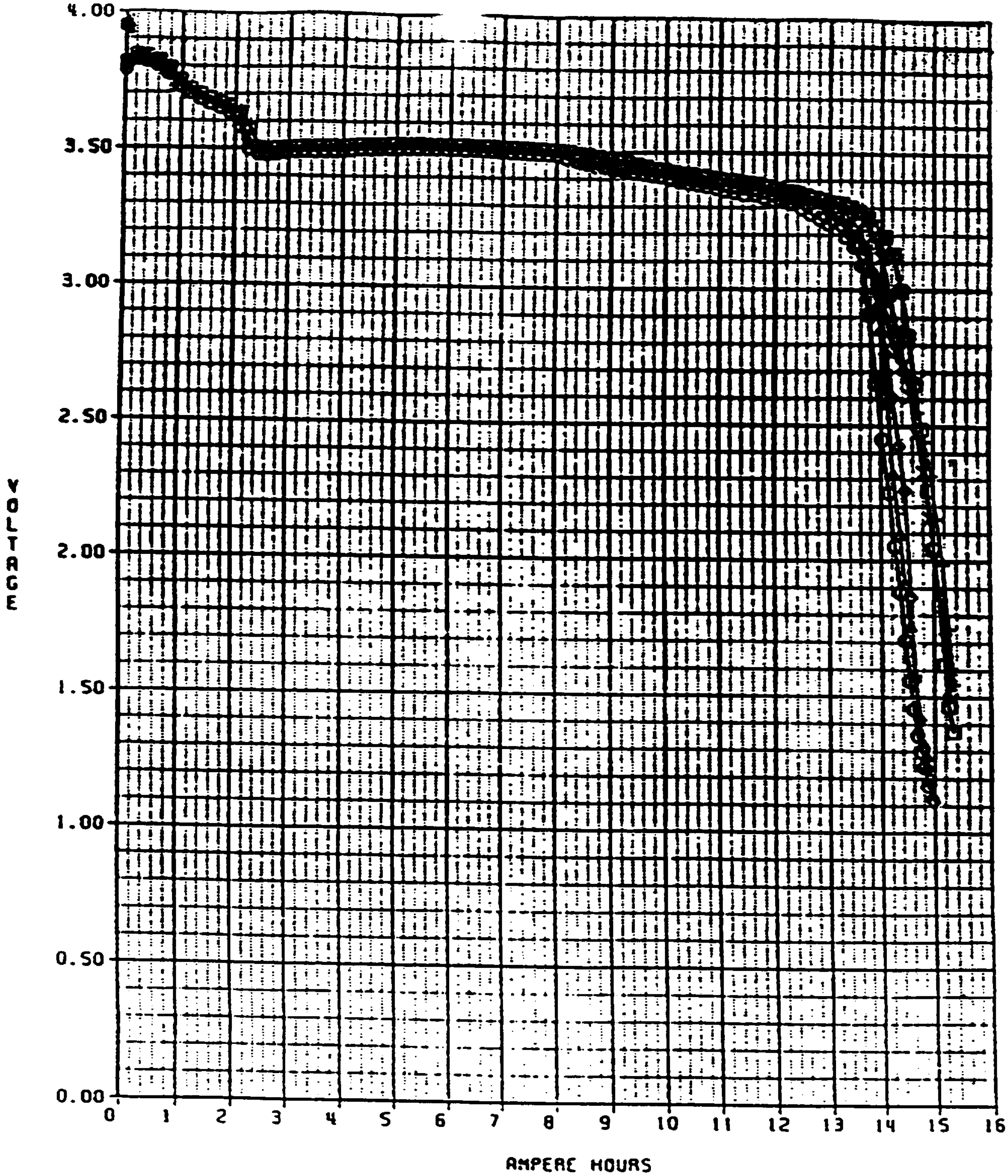


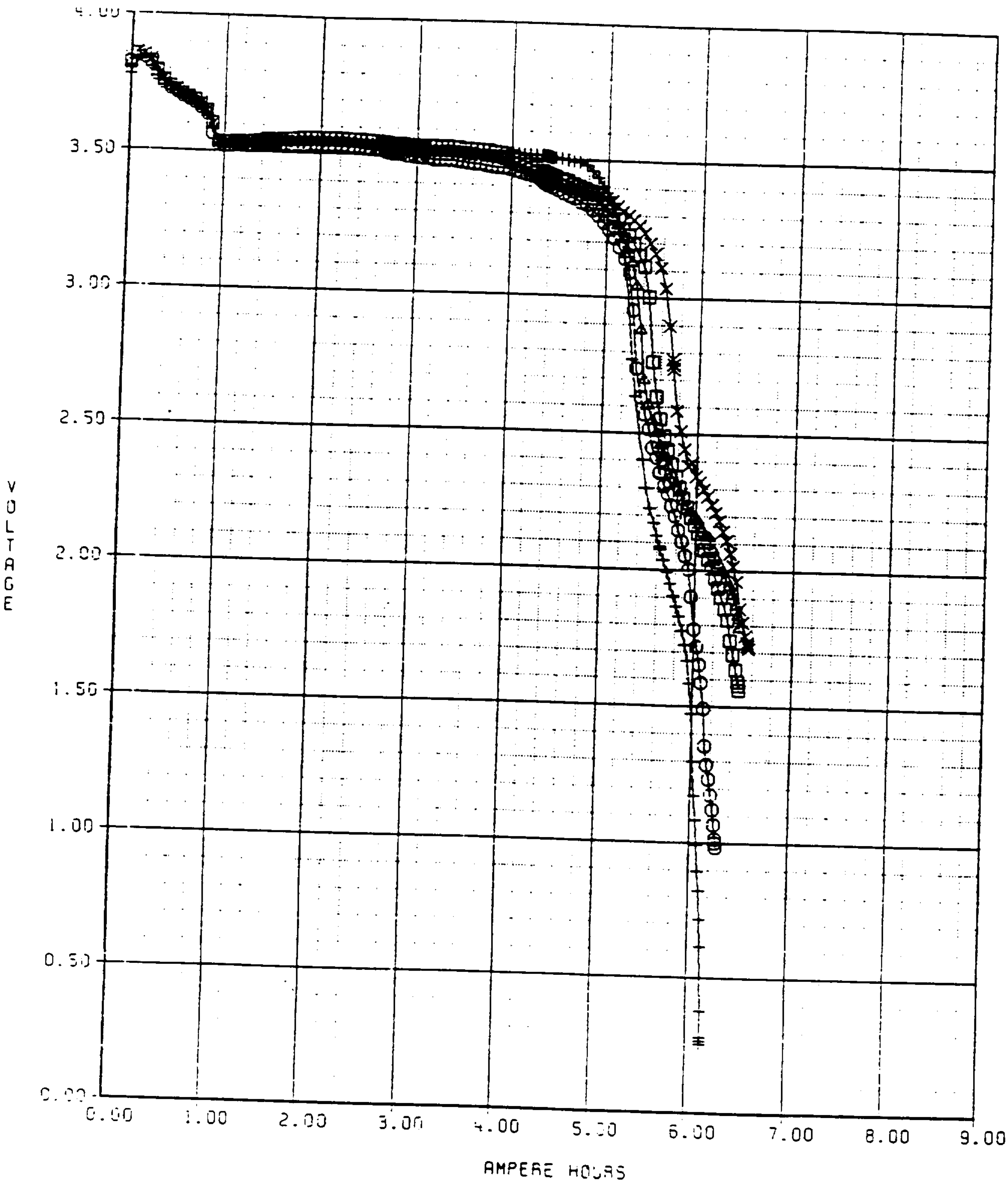
Figure 10. Discharge curves of a group of D cells (redesign III, production build), discharged under a 20 ohm constant load.

FIGURE 6. W. CLARK

Results of Temperature Exposure Tests for Redesigned C Cells

Cell #	State	Height Change (inches)	Result
27993	BOL	.009	Passed
27994	BOL	.015	Passed
27995	BOL	.012	Passed
27996	BOL	.022	Passed
27998	BOL	.012	Passed
27999	BOL	.013	Passed
28001	BOL	.011	Passed
28002	BOL	.016	Passed
28009	BOL	.002	Passed
28010	BOL	.023	Passed

FIGURE 7. W. CLARK



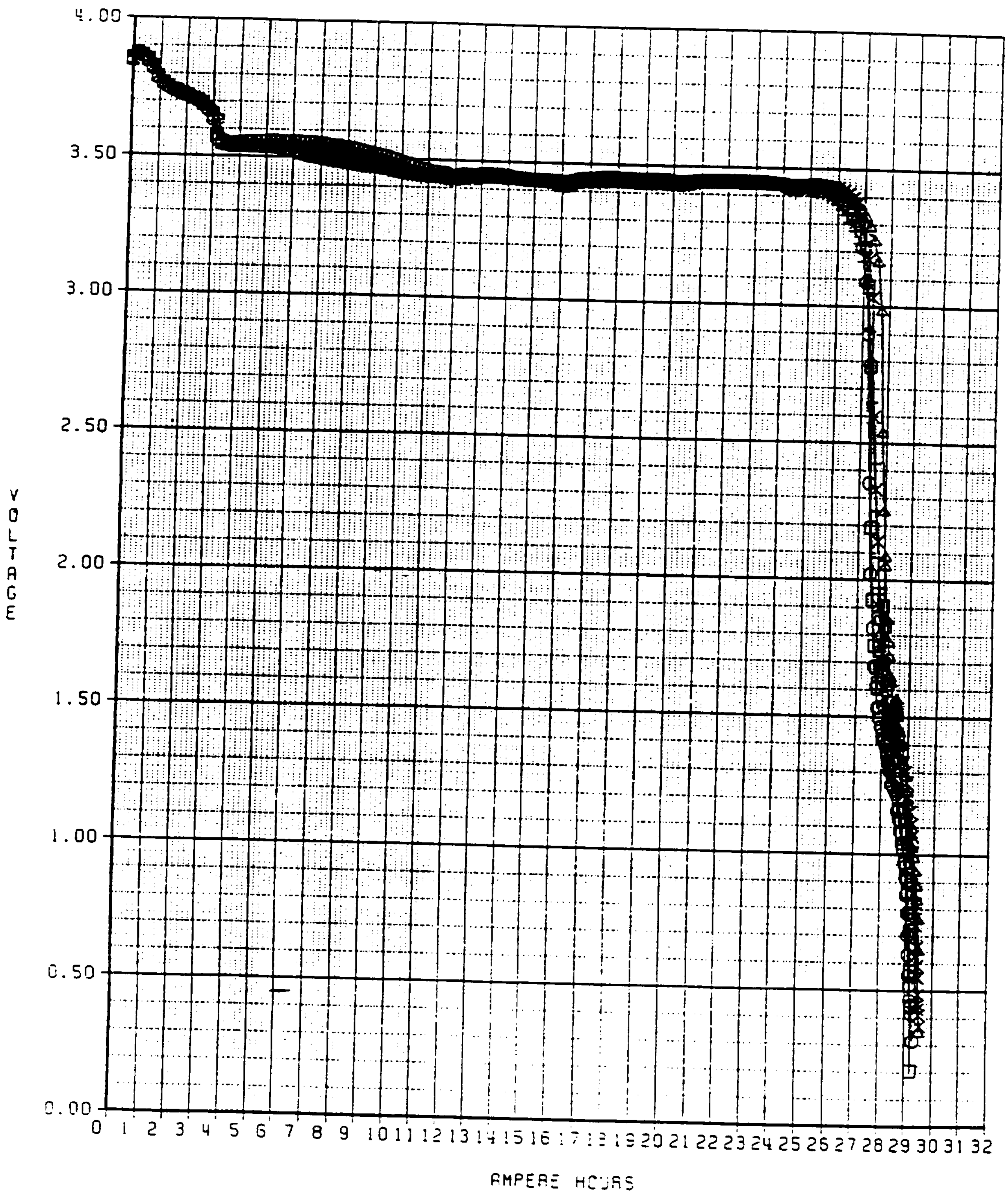
Discharge curves of a group of redesigned C cells discharged under a 56.2 Ω constant load.

FIGURE 8. W. CLARK

Results of Temperature Exposure Tests for Redesigned DD Cells

Cell#	State	Height Change (inches)	Result
28021	BOL	.005	Passed
28022	BOL	.022	Passed
28023	BOL	.011	Passed
28024	BOL	.004	Passed
28025	BOL	.013	Passed
28026	BOL	.002	Passed
28027	BOL	.024	Passed
28028	BOL	.006	Passed
28029	BOL	.014	Passed
28030	BOL	.015	Passed

FIGURE 9. W. CLARK



Discharge curves of a group of redesigned DD cells discharged under a 20 Ω constant load.

FIGURE 10. W. CLARK

Experimentally Determined Values for the Heat Capacities of BCX 72 D Size Batteries.

Battery	Experimentally Measured Heat Capacities (cal / g °K)				
	run 1	run 2	run 3	average	precision (% difference)
BOL 1	0.251	0.243	0.245	0.246	2.03%
BOL 2	0.239	0.241	0.231	0.237	2.53%
BOL 3	0.253	0.251	0.241	0.252	0.4%
(1/2) 1	0.235	0.231	0.236	0.234	1.28%
(1/2) 2	0.242	0.241	0.252	0.245	2.86%
(1/2) 3	0.240	0.234	0.234	0.236	1.69%
EOL 1	0.255	0.241	0.252	0.249	2.41%
EOL 2	0.219	0.220	0.217	0.219	0.91%
EOL 3	0.253	0.252	0.253	0.253	0.40 %

FIGURE 11. W. CLARK

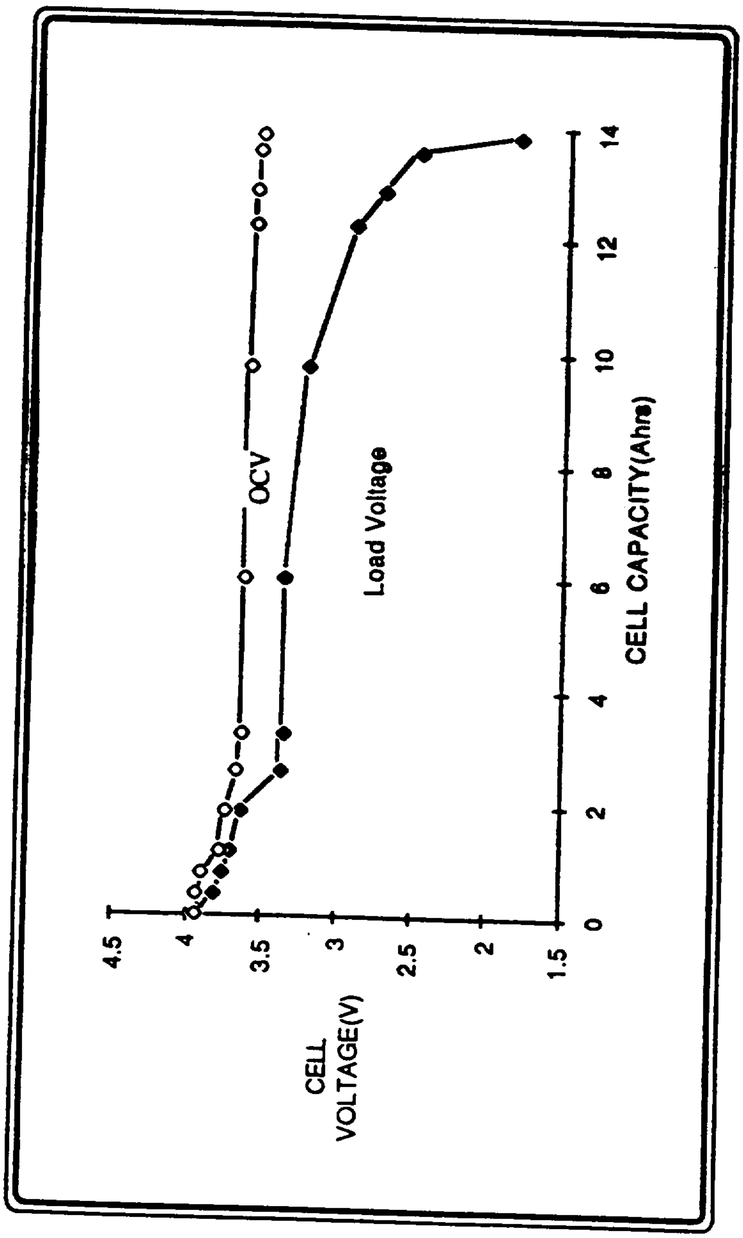


FIGURE 12. W. CLARK

Results of Adiabatic Discharge Experiments.

S/N	LOAD (Ω)	V_{ave} (V)	ΔV (V)	I_{ave} (A)	T_{init} (°C)	T_{fin} (°C)	Duration (hours)
1619	1.50	2.88	0.77	1.92	19.00	63.00	0.98
1624	1.50	2.84	0.81	1.89	19.50	65.50	0.97
1621	2.00	2.97	0.68	1.49	21.00	62.50	1.50
1625	2.00	2.95	0.70	1.48	21.00	64.00	1.50
1616	5.00	3.19	0.46	0.64	25.00	47.00	3.00
1622	5.00	3.18	0.47	0.64	25.00	44.00	3.00
1617	3.00	3.07	0.58	1.02	25.50	55.00	1.98
1623	3.00	3.09	0.56	1.03	26.00	55.00	1.98
1618	10.00	3.28	0.37	0.33	22.40	33.00	6.00
1620	10.00	3.24	0.41	0.32	22.40	33.00	6.00

FIGURE 13. W. CLARK

Heat Capacities as Determined by Adiabatic Discharge

Heat Evolved (cal/gr.)	Temperature Rise (°C)	Heat Capacity cal/deg/g
10.83	44.00	0.25
11.12	46.00	0.24
11.33	41.50	0.27
11.58	43.00	0.27
6.58	22.00	0.30
6.71	19.00	0.35
8.79	29.50	0.30
8.54	29.00	0.29
5.45	10.60	0.51
5.96	10.60	0.56

FIGURE 14. W. CLARK

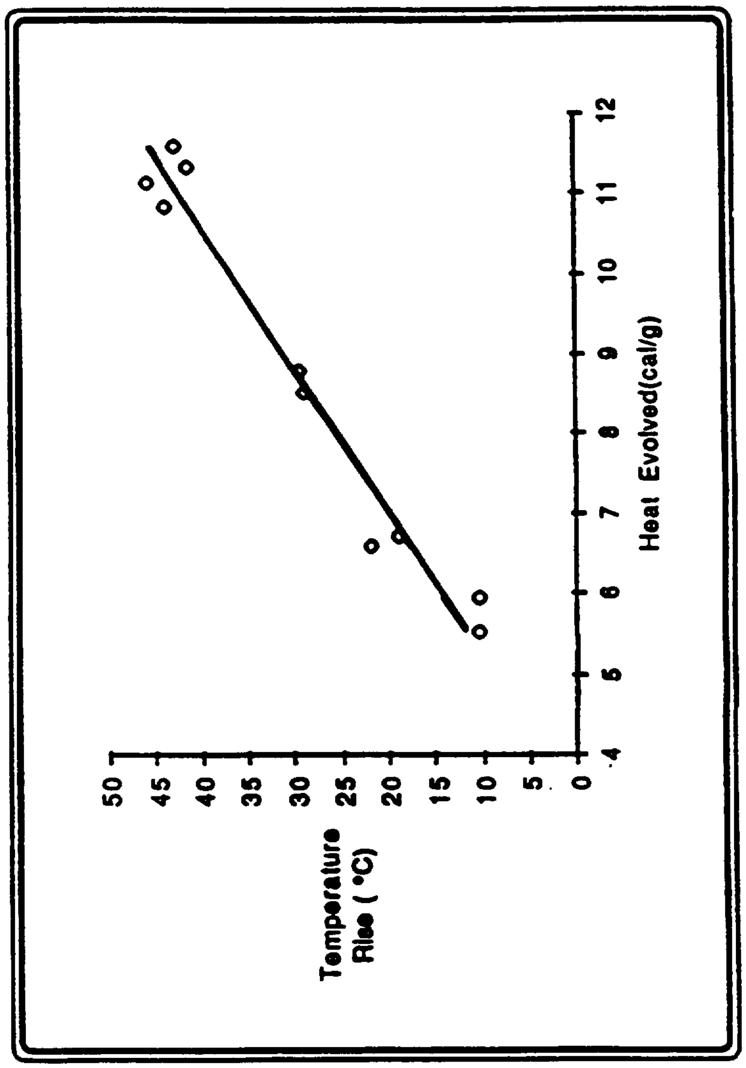


FIGURE 15. W. CLARK

Acknowledgements

This work was funded under NASA contract NAS 9-17701 administered by the Johnson Space Flight Center. The heat capacity determinations were done by Professor K. J. Takeuchi, assisted by Mr. S. A. Kubow and Mr. R. A. Leising of the Department of Chemistry of SUNY Buffalo under contract to Wilson Greatbatch Ltd. The authors also thank Mr. R. C. Stinebring for the supervision of the cell testing.

FIGURE 16. W. CLARK

WEDNESDAY, NOVEMBER 4, 1987
(AFTERNOON SESSION)

"QUALITY ASSURANCE REQUIREMENTS FOR A LARGE $Li/SOCL_2$ BATTERY FOR SPACECRAFT APPLICATIONS"

RICHARD MAURER

Chairman Gerald Halpert introduced the first speaker of the afternoon, Richard Maurer of Johns Hopkins/APL. Maurer spoke on "Quality Assurance Requirements for a Large $Li/SOCl_2$ Battery for Spacecraft Applications."

Currently APL is building a spacecraft for SDI. It will fly early next year on a short mission. There were about two years from start of program to launch. The emphasis is on quality assurance for the cells. (They abandoned AgZn and switched to lithium.)

Program objectives are shown in Maurer [Figure 4]. It is important to minimize the variation of cell capacity within flight battery modules. The module circuit configuration features two diodes. There is one thermal fuse for three cells, and thus a total of three fuses in the module/submodule configuration (Maurer [Figure 6]).

The $Li/SOCl_2$ fault tree, (Maurer [Figure 8]) shows the biggest failure probabilities at the bottom, so that's the place to concentrate for improvements. Maurer [Figure 10], labelled Probability of Low Cell Capacity, shows what can be gained by controlling the manufacturing process. It explains how the numbers can be arrived to change from ten percent variation down to five percent. The Cell Acceptance Test Flow Chart, (Maurer [Figure 11]), explains the control methods that were used. In the cell lot qualification test, 183 cells were short circuited with no hazard. The Data Base chart (Maurer [Figures 13 and 14]), shows the basis for rejecting cells. Some cells were rejected because the serial number was smudged. Cells that were either x-ray rejects or had high or low electrolyte fill weights were not accepted under any conditions.

The Delta 181 cell discharge test (Maurer [Figure 15]), was performed on about 20 cells. Black blots in the normal probability plot show the sample size (Maurer [Figure 17 and 19]).

In studying F cell capacities at 2 and 4 amps, (Maurer [Figure 18, 20 and 21]) there was a notable variation in discharge rates. The vibration tests, which were performed right after the capacity measurements, showed a slightly greater capacity.

In the Waller-Duncan Multiple Range Test, (Maurer [Figure 22]), lots belonging to the same letter group do not vary significantly. The study concentrated on the groups having the highest outputs. The lot numbers started with "1"--new numbers were assigned after weekend breaks, etc.

Q. Gowdey (NASA Langley): What were the vibration levels and how were they established?

A. The vibrations were random--no special requirements. It was a manufacturing screening level.

Q. Swette (Giner, Inc.): Who was the manufacturer?

A. Altus was the manufacturer.

QUALITY ASSURANCE REQUIREMENTS FOR A LARGE Li/$SOCL_2$ BATTERY FOR SPACECRAFT APPLICATIONS

O. MANUEL UY AND RICHARD H. MAURER

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
JOHNS HOPKINS ROAD
LAUREL, MARYLAND 20707

PRESENTED AT
1987 NASA/GSFC BATTERY WORKSHOP
GREENBELT, MARYLAND

NOVEMBER 4, 1987

FIGURE 1. MAUER

OUTLINE

A. INTRODUCTION AND OBJECTIVES

B. HARDWARE DESCRIPTION

C. QUALITY ASSURANCE CONSIDERATIONS

D. EXPERIMENTAL RESULTS

E. CONCLUSIONS

FIGURE 2. MAUER

INTRODUCTION

- CURRENT SPACECRAFT PROGRAM REQUIRES A 2000 AMP-HOUR, 450 lb. BATTERY
- MISSION OBJECTIVES CAN ONLY BE ACHIEVED WITH $Li/SOCL_2$ CHEMISTRY
- BATTERY IS COMPOSED OF 15 MODULES — THREE PANELS OF FIVE MODULES EACH
- EACH MODULE HAS EIGHT SUBMODULES OF NINE F CELLS
- 1080 F CELL BATTERY

FIGURE 3. MAUER

OBJECTIVES

- FIRST PHASE (FALL 1986) PERFORM A SAFETY FAULT TREE ANALYSIS OF THE BATTERY
- FAULT TREE ANALYSIS SHOWED THE IMPORTANCE OF MINIMIZING THE VARIATION OF CELL CAPACITY
- FLIGHT BATTERY MODULES SHOULD BE COMPOSED OF CELLS FROM THE SAME MANUFACTURING LOT TO MINIMIZE VARIATION WITHIN THE MODULE
- APPLY STATISTICAL METHODS OF QUALITY CONTROL TO SELECT PREFERRED MANUFACTURING LOTS

FIGURE 4. MAUER

MODULE ORIENTATION RELATIVE TO SPACECRAFT AXES

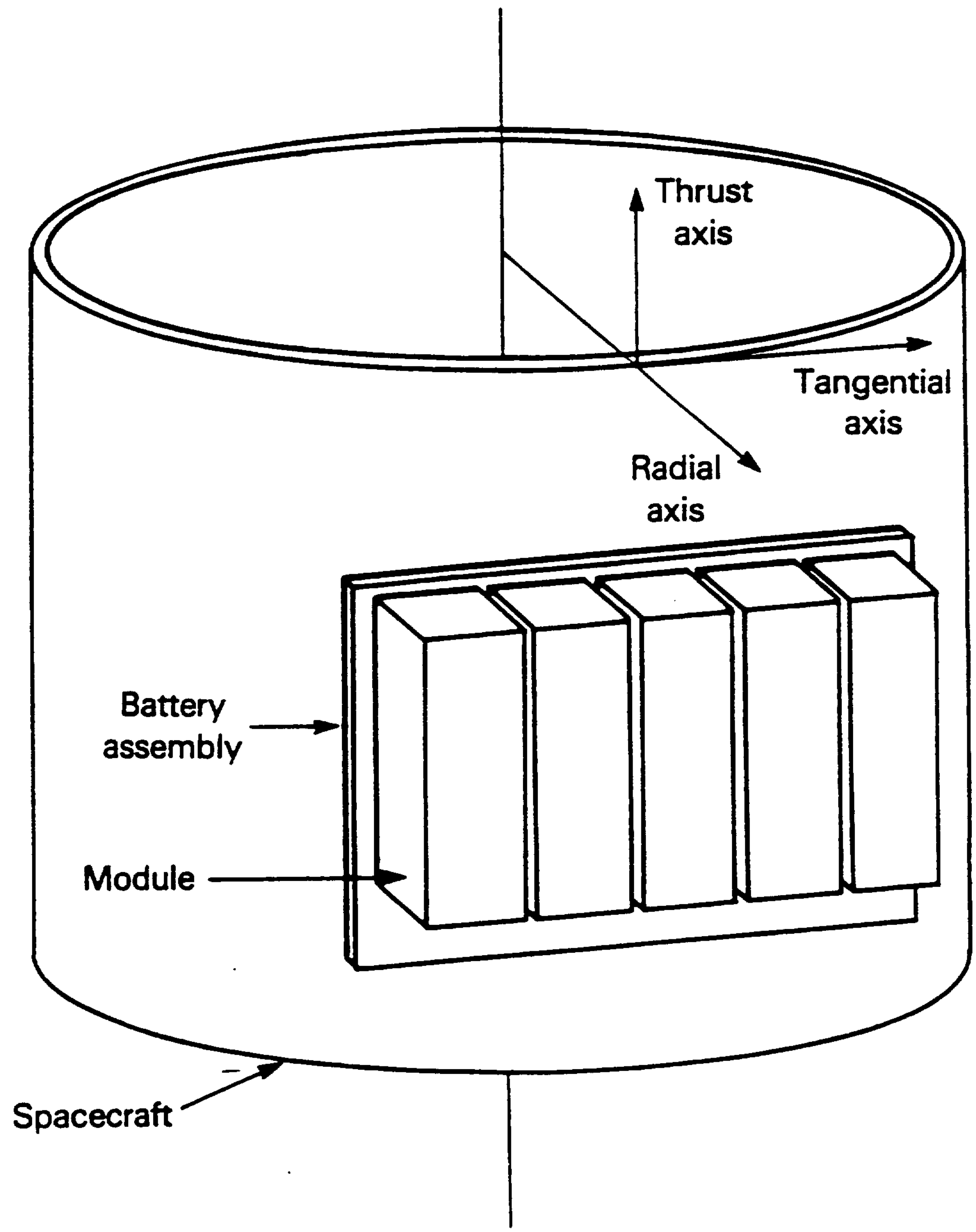


FIGURE 5. MAUER

MODULE CIRCUIT CONFIGURATION

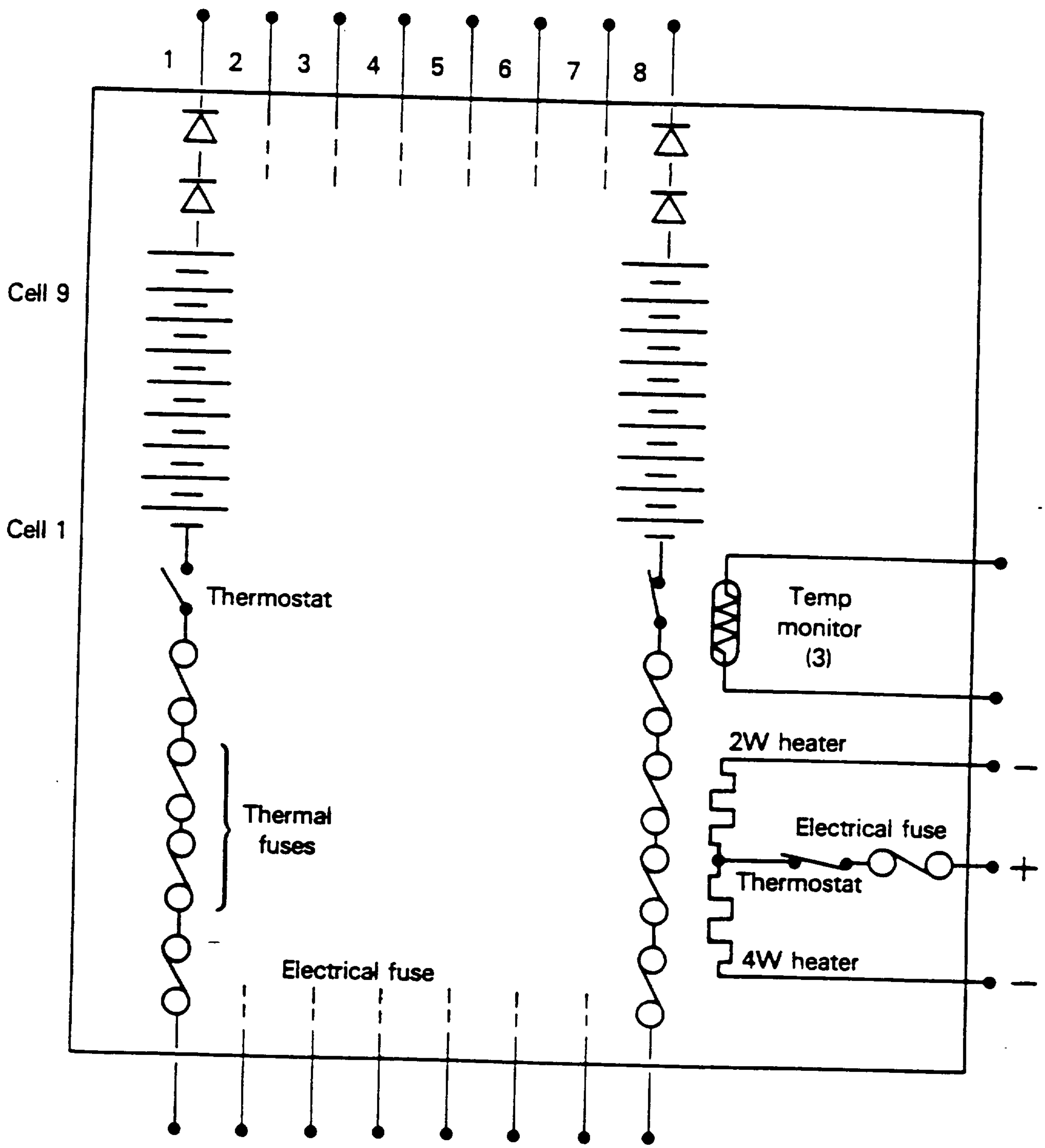


FIGURE 6. MAUER

MODULE AND SUBMODULE CONFIGURATION

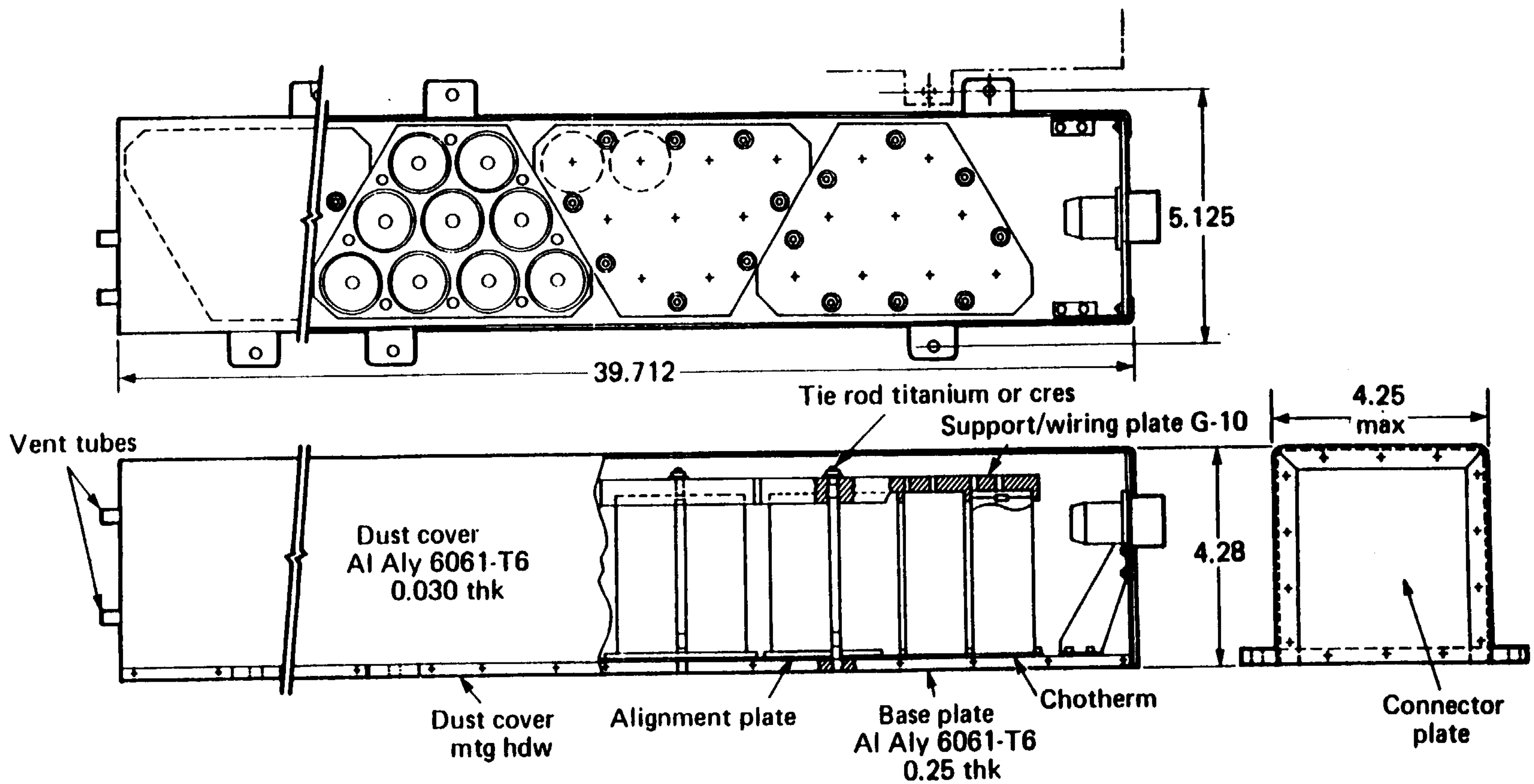


FIGURE 7. MAUER

$LiSOCl_2$ SINGLE CELL SAFETY FAULT TREE FOR SPACECRAFT

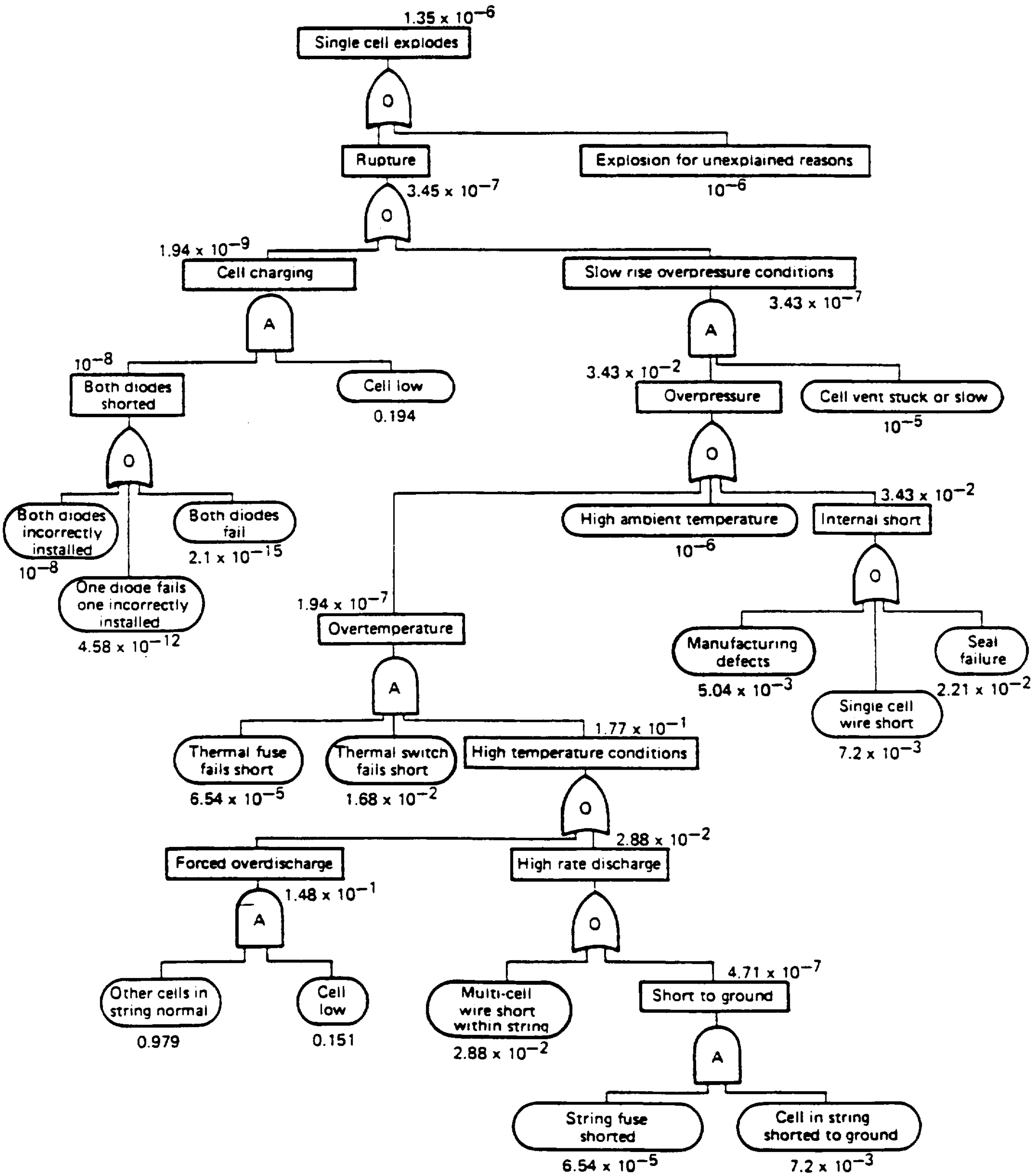


FIGURE 8. MAUER

BATTERY MODULE SAFETY FAULT TREES FOR GROUND INTEGRATION

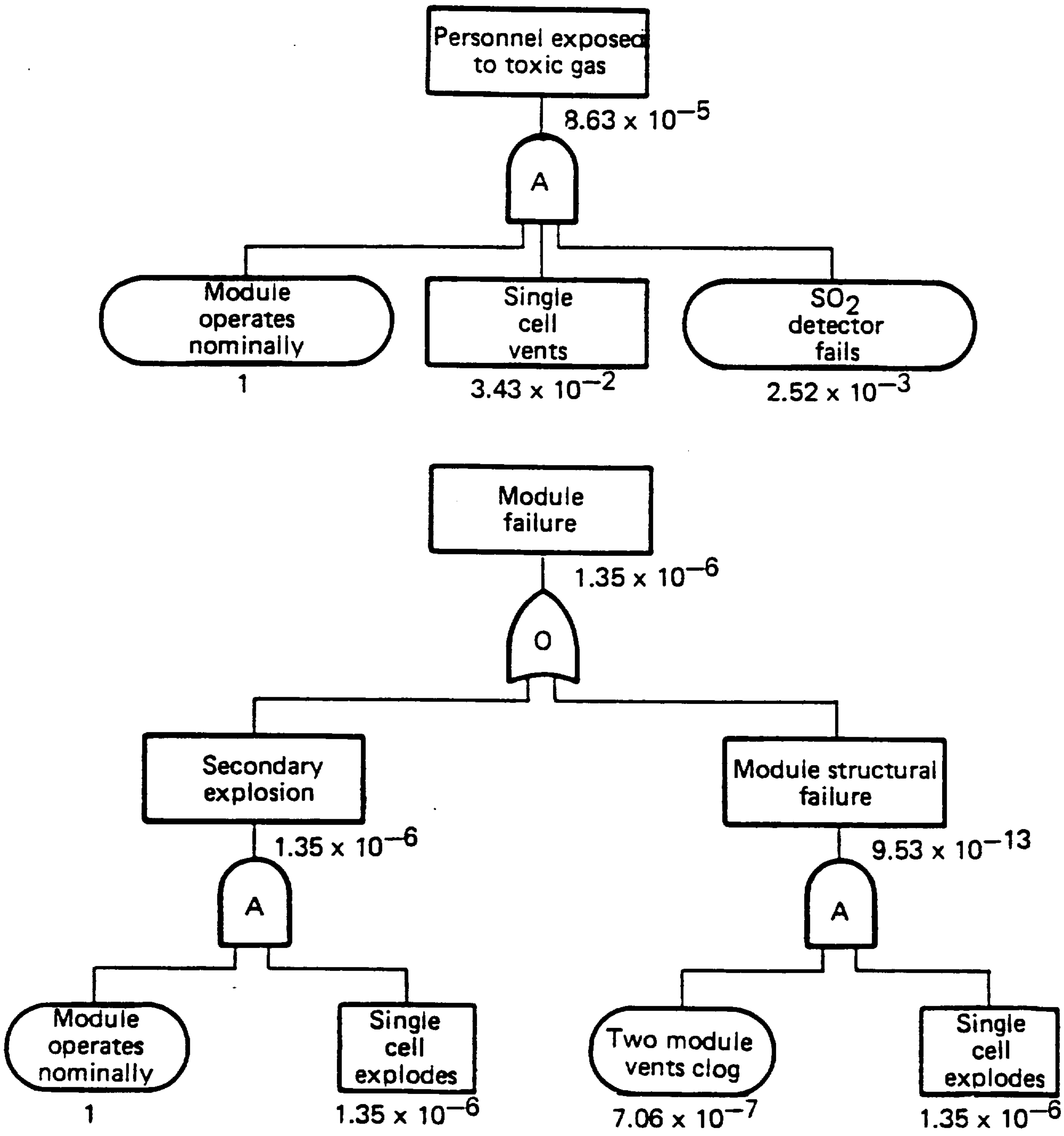


FIGURE 9. MAUER

PROBABILITY OF LOW CELL CAPACITY (ZERO CAPACITY AT 75% OF MISSION LIFE)

COEFFICIENT OF VARIATION $\sigma/\bar{X}$	STANDARDIZED NORMAL VARIATE Z	PROBABILITY OF ZERO CAPACITY	RATIO
0.10	2.50	6.2×10^{-3}	~20,000/1
0.05	5.00	2.87×10^{-7}	—

$$Z = \text{(MEAN-LOWER LIMIT)/STANDARD DEVIATION}$$
$$= (\bar{X} - LL)/\sigma$$
$$= (1 - LL/\bar{X})/\sigma/\bar{X})$$
$$= 0.25/CV$$

FIGURE 10. MAUER

CELL ACCEPTANCE TEST FLOW CHART

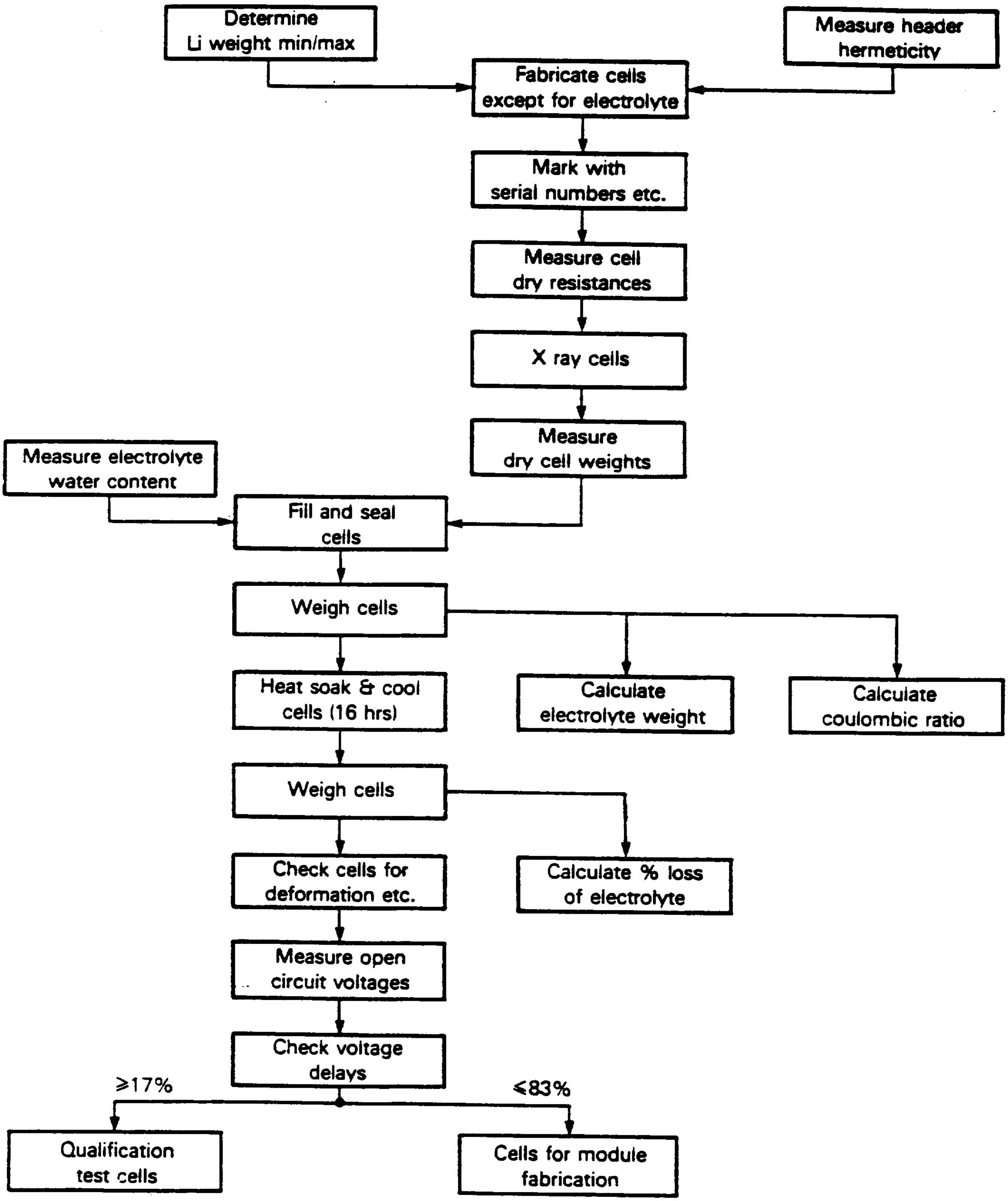


FIGURE 11. MAUER

CELL LOT QUALIFICATION TEST AND CERTIFICATION FLOW CHART

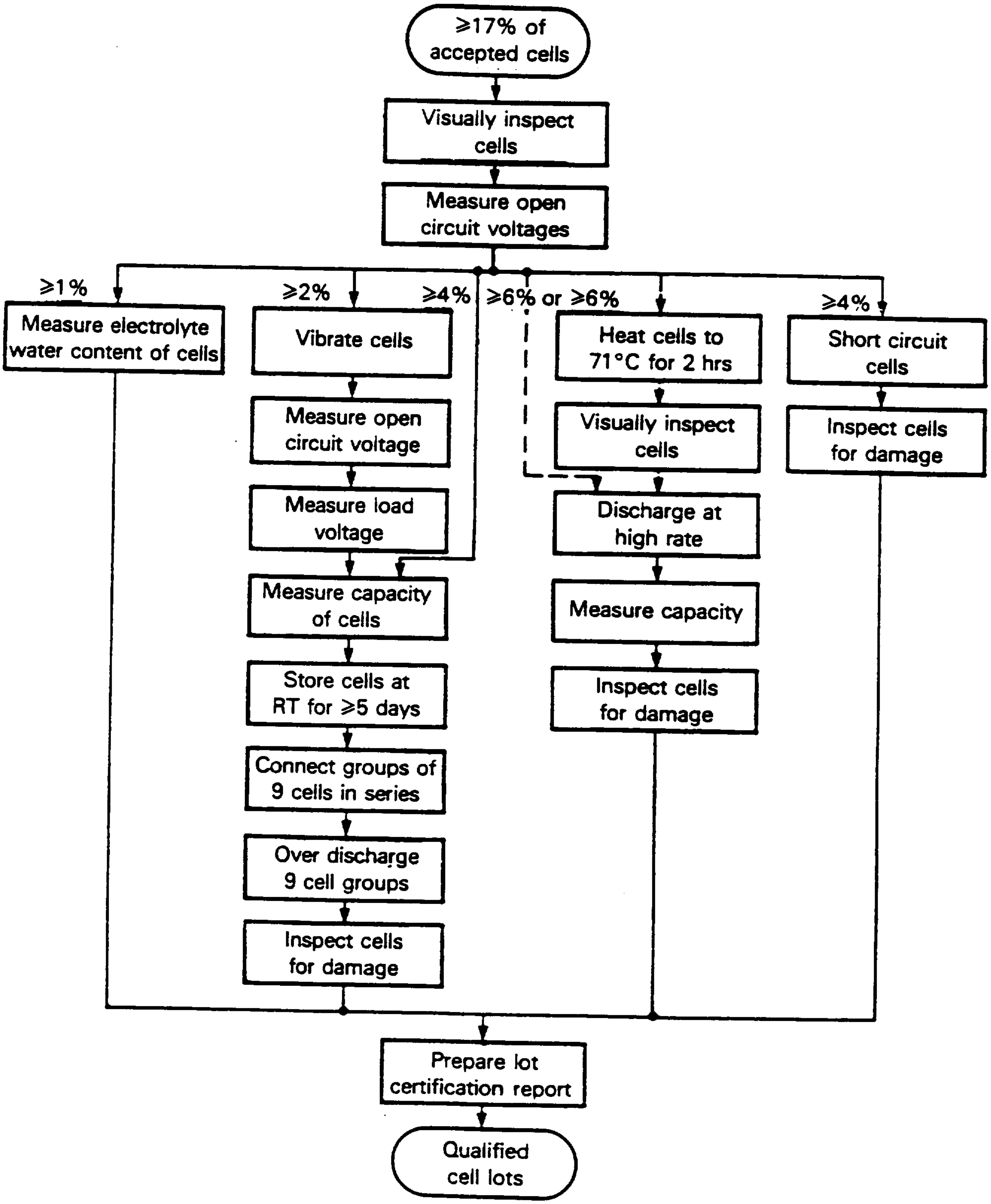


FIGURE 12. MAUER

DATA BASE

- 6600 F CELLS MANUFACTURED

NON-DESTRUCTIVE TESTS

- 363 CELLS REJECTED BY X-RAY
- 336 CELLS REJECTED BY ELECTROLYTE WEIGHT LOSS OR MISSING DATA
- 265 CELLS REJECTED BY VOLTAGE UNDER LOAD TEST
- 214 CELLS REJECTED FOR FILL WEIGHTS $>$ 62 gms OR $<$ 58 gms
- 101 CELLS REJECTED FOR TAB PULL TEST
- 23 CELLS REJECTED FOR OTHER REASONS

DESTRUCTIVE TESTS

- 223 CELLS DISCHARGED AT 2 AMPS
- 305 CELLS DISCHARGED AT 4 AMPS
- 116 CELLS DISCHARGED AT 2 AMPS AFTER RANDOM VIBRATION
- 183 CELLS SHORT-CIRCUITED
- 72 CELLS DESTROYED DURING HEAT TAPE TEST

FIGURE 13. MAUER

BECAUSE MISSION REQUIRES MORE (+33%) POWER, ADDITIONAL CELLS WERE RECOVERED FROM THE NON-DESTRUCTIVE TESTING REJECTS. THESE ARE FOR DESTRUCTIVE MODULE TESTS ONLY, NOT FOR FLIGHT

311/336 CELLS ACCEPTED AFTER REBAKE

249/265 CELLS ACCEPTED BY REDUCING VOLTAGE UNDER LOAD FROM 2.8 TO 2.5 VOLTS

98/101 CELLS RETABBED AND RETESTED

NOT ACCEPTED UNDER ANY CONDITIONS:

- X-RAY REJECTS
- HIGH OR LOW ELECTROLYTE FILL WEIGHTS

FIGURE 14. MAUER

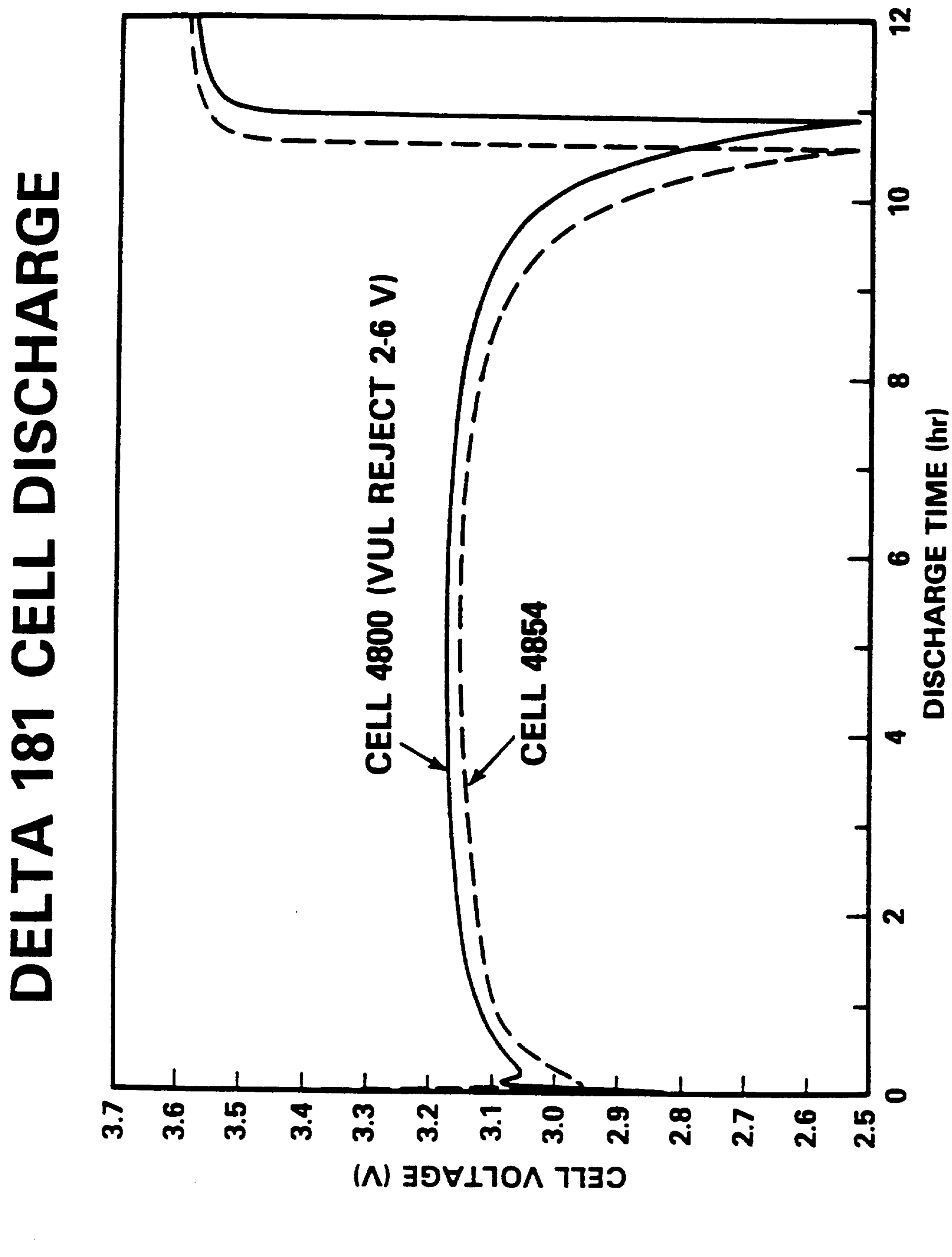
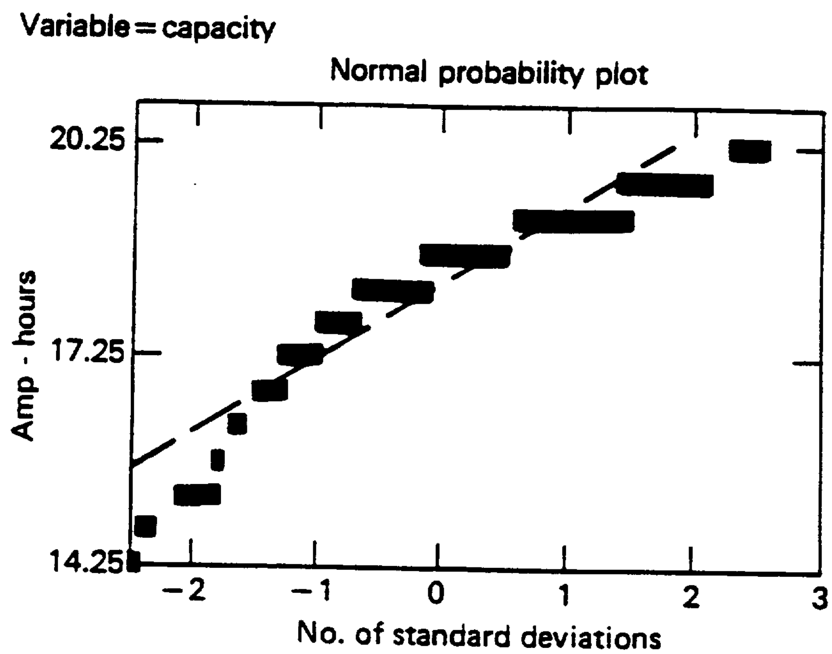


FIGURE 15. MAUER

HYPOTHESES

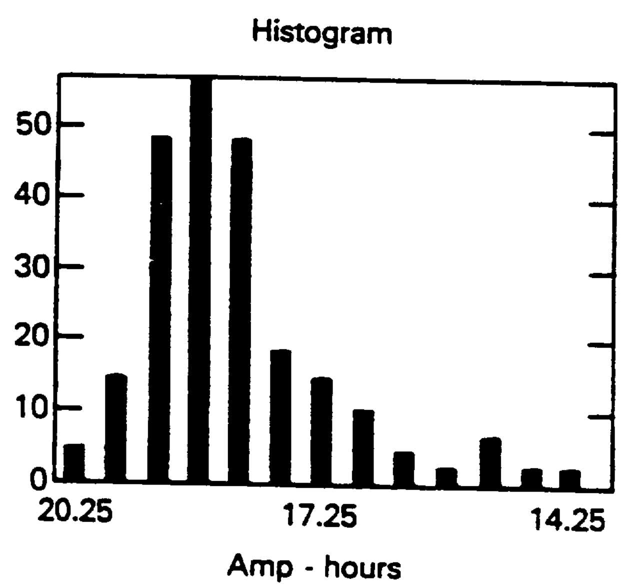
- CELL CAPACITIES ARE NORMALLY DISTRIBUTED
- CELL CAPACITY IS INDEPENDENT OF VARIATIONS IN MANUFACTURING PARAMETERS SUCH AS FILL LEVEL, COULOMBIC RATIO, LITHIUM ANODE WEIGHT, ETC., AT A 95% CONFIDENCE LEVEL
- WALLER-DUNCAN MULTIPLE RANGE TEST AT A 95% CONFIDENCE LEVEL USED TO DETERMINE WHICH MANUFACTURING LOTS OF CELLS, IF ANY, ARE SIGNIFICANTLY DIFFERENT FROM EACH OTHER

FIGURE 16. MAUER



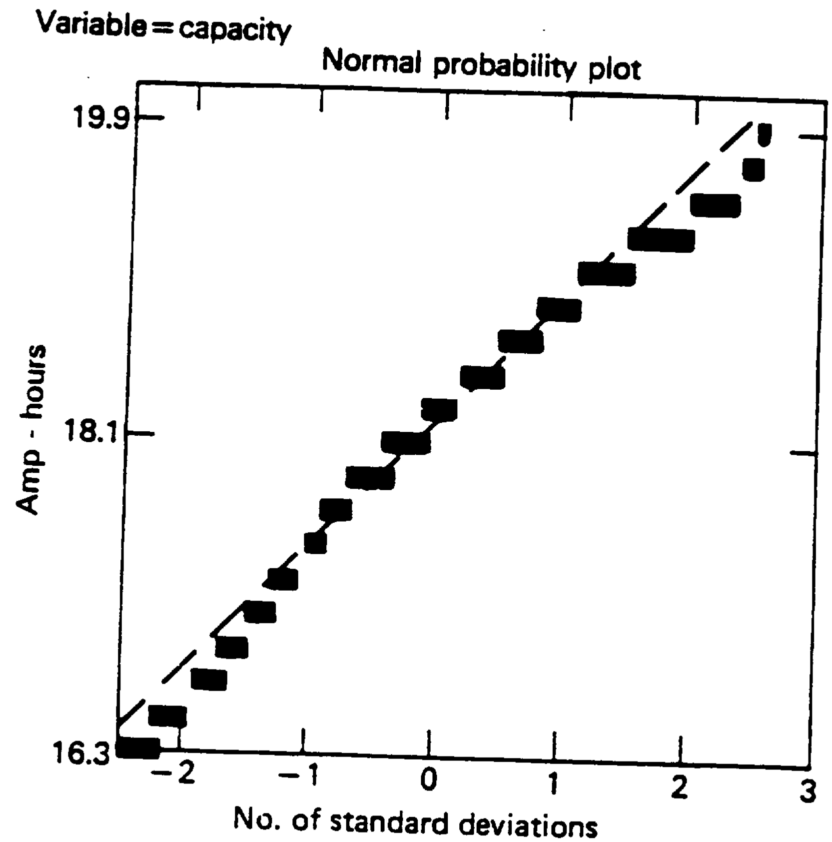
NORMAL PROBABILITY PLOT OF 2 AMP F CELL CAPACITY

FIGURE 17. MAUER



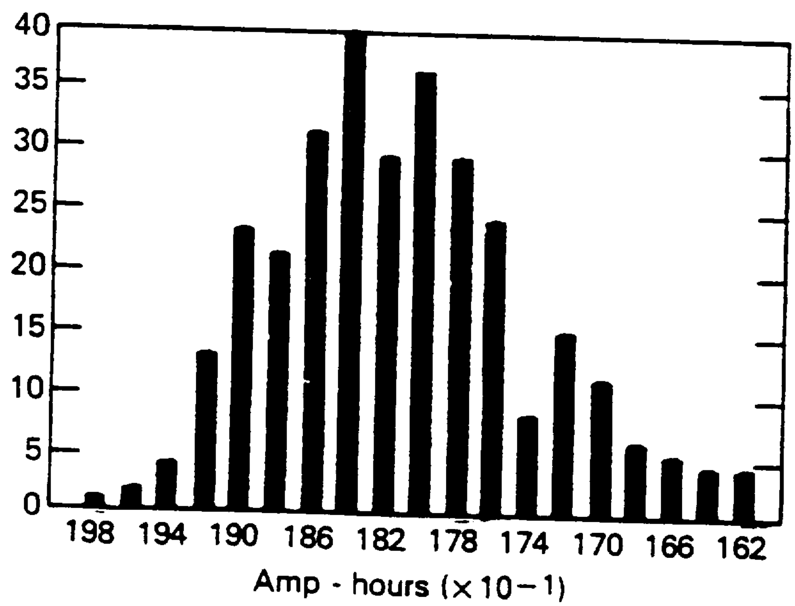
HISTOGRAM OF 2 AMP F CELL CAPACITY

FIGURE 18. MAUER



NORMAL PROBABILITY LOT OF 4 AMP F CELL CAPACITY

FIGURE 19. MAUER



HISTOGRAM OF 4 AMP F CELL CAPACITY

FIGURE 20. MAUER

F CELL CAPACITIES AT 2 AND 4 AMPS

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: CAP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	22	194.41368410	8.83698564	12.24	0.0001
ERROR	642	463.41140158	0.72182461		
CORRECTED TOTAL	664	657.82508568			
	R-SQUARE	C.V.	ROOT MSE		CAP MEAN
	0.295540	4.6072331	0.84960262		18.44062597

SOURCE	DF	ANOVA SS	MEAN SQUARE	F VALUE	PR > F
LOTNO	10	33.87803	3.38780	4.69	0.0001
AMP	1	51.96687	51.96687	71.99	0.0001
VIBN(AMP)	1	46.54828	46.54828	64.49	0.0001
LOTNO*AMP	10	62.02050	6.20205	8.59	0.0001

FIGURE 21. MAUER

WALLER-DUNCAN MULTIPLE RANGE TEST

GROUPING*	MEAN CAPACITY (AMP-HR)	SAMPLE SIZE	LOT NUMBER
A	18.89	53	11
A B	18.67	58	10
A B	18.65	68	5
B C	18.54	85	9
B C	18.51	52	7
B C D	18.39	54	3
B C D	18.36	57	6
C D	18.31	71	4
C D	18.28	59	2
D	18.10	73	8
D	18.09	35	1

*MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT AT THE 95% CONFIDENCE LEVEL.

FIGURE 22. MAUER

CONCLUSIONS

- LITHIUM THIONYL CHLORIDE F CELL HAS A MEAN CAPACITY OF 18 AMP-HOURS
- MANUFACTURING LOTS 11,10,5,9,7, AND 6 HAVE COEFFICIENTS OF VARIATION LESS THAT 5% UNDER ALL CAPACITY TEST CONDITIONS
- WALLER-DUNCAN GROUPING SHOWS THAT LOTS 11,10,5,9,7,3, AND 6 BELONG TO THE TWO HIGHEST WALLER GROUPS WITH RESPECT TO MEAN CELL CAPACITY
- PREFERRED LOTS 11,10,5,9, AND 7 YIELD ENOUGH CELLS FOR THE FLIGHT AND SPARE BATTERY MODULES
- MEAN CAPACITY AFTER RANDOM VIBRATION IS SIGNIFICANTLY GREATER THAN THAT WITHOUT VIBRATION
- EXTENSIVE ANALYSIS OF VARIANCE ON MANUFACTURING PARAMETERS SHOWED THAT THESE WERE ADEQUATELY CONTROLLED SO THAT VARIATIONS IN CAPACITY WERE DUE TO RANDOM EFFECTS ALONE

FIGURE 23. MAUER

"PACKAGING OF A LARGE $Li/SOCL_2$ BATTERY FOR CENTAUR"

VIC KARDARPA

The next paper was by Vic Kardarpa of General Dynamics on "Packaging of a Large $Li/SOCl_2$ Battery for Centaur." This paper was previously presented at the IECEC conference and also at GSFC last year.

AgZn batteries that are used on Centaur need to be replaced by lighter batteries with higher capacities. The 250 amp-hour $LiSOCl_2$ battery program, (Kardarpa [Figure 3]), started about two years ago with Air Force sponsorship. Four cells were built and tested, leading to a design evaluation and status report. Then 16 cells and 2 batteries were fabricated and carried through test and evaluation and design. The 250 amp-hour cell design features are shown in (Kardarpa [Figure 5]). The next set of cells to be designed may not use catalytic copper in the cathodes.

Four lithium batteries were built for the functional interchange test (Kardarpa [Figure 6]). One cell was placed on a steel slab to test heat discharge. Another was placed on a piece of wood at ambient room conditions. A third was kept under adiabatic conditions. The conclusion of the work is that it is possible to build a 250 amp-hour lithium/thionyl chloride cell that can be used safely on Centaur (Kardarpa [Figure 10]).

Kardarpa reviewed a program of 9-cell battery packaging for Centaur. There is no decision on using copper. The design is to optimize container wall thickness. In preparing the curves for 9-cell lithium battery characteristics, 1/4 volt has been taken off for discharge losses (Kardarpa [Figure 16]). Regarding heat inputs to the battery, little attention was paid to entropy effects (Kardarpa [Figure 17]).

With the 250 amp-hour thermal model it was found that temperatures dropped constantly in the worst-case cold environment even though current was added (Kardarpa [Figure 21]). Again with the model, but now applied to worst-case hot, temperatures could go to 120 degrees C at the end of the mission (Kardarpa [Figure 23]).

Kardarpa concluded that worst-case cold could be a problem below -15 degrees C. He saw no safety problems, and there could be a 50 percent reduction in weight compared to AgZn. Shock, vibration, and thermal vacuum tests remain to be performed.

Q. Youngblood (GE Americom): Are you measuring internal pressure changes during the tests?

A. Yes, but only at the high temperatures.

Q. ______?: What happens when you short out one of the four cells?

A. That will be done in the next test.

A. Halpert (JPL): We can always make the cells blow up, but we try to balance performance with safety.

PACKAGING OF A LARGE
LITHIUM/THIONYL CHLORIDE BATTERY
FOR SPACE LAUNCH VEHICLES

GENERAL DYNAMICS
Space Systems Division

FIGURE 1. KARDARPA

MOTIVATION

INCREASE IN SPACECRAFT PAYLOAD WEIGHTS

INCREASE IN DEEPER SPACE LAUNCHES

INCREASE IN MISSION TIMES

REQUIRE

LARGE ELECTRICAL POWER SYSTEMS

LIGHTER BATTERIES WITH HIGHER CAPACITIES

OR BATTERIES WITH HIGH ENERGY DENSITIES

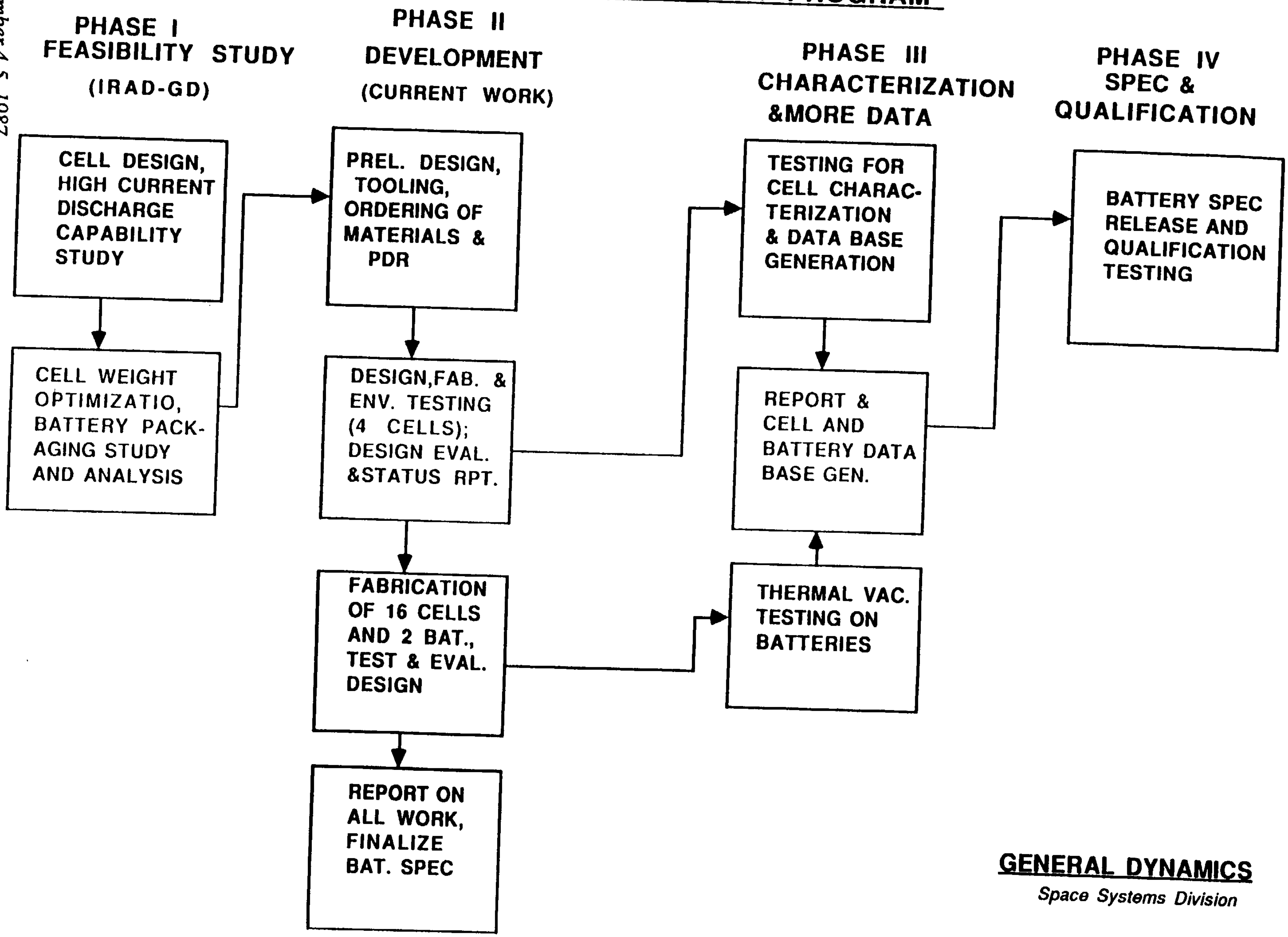
AND CAPABLE OF HIGH DISCHARGE RATES

GENERAL DYNAMICS

Space Systems Division

FIGURE 2. KARDARPA

250 AH Li/SOCl2 BATTERY PROGRAM



GENERAL DYNAMICS
Space Systems Division

OBJECTIVES OF STUDY

1. DEVELOP AND TEST 250 AH CELLS
   - ACTIVE PRIMARY
2. PACKAGE 9 CELLS INTO A BATTERY
   -FIXED SPACE; WEIGHT CRITICAL
3. PERFORM MECHANICAL ANALYSIS
   -LAUNCH ENVIRONMENT
4. PERFORM THERMAL ANALYSIS
   - DEEP SPACE

GENERAL DYNAMICS
Space Systems Division

FIGURE 4. KARDARPA

250 AH CELL DESIGN FEATURES (A FEASIBILITY STUDY)

1. CYLINDRICAL CELLS - AN ALTUS DESIGN
2. BIELECTRODE STACKING - CATHODE LIMITED DESIGN
3. CATHODE - CARBON WITH 20% CATALYTIC COPPER
4. ELECTROLYTE - 1.6 M $LiAlCl_4$ IN $SOCl_2$
5. SUBSTANTIAL EXCESS ELECTROLYTE
6. SPECIAL EMPHASIS IN BUSSING DESIGN
7. LOW INTERNAL IMPEDANCE

GENERAL DYNAMICS
Space Systems Division

FIGURE 5. KARDARPA

GENERAL DYNAMICS
Space Systems Division

FUNCTIONAL INTERCHANGE, LITHIUM BATTERIES

TEST SET-UP DESCRIPTION

-TEST PROFILE	4 CYCLES, 1 HOUR DURATION EACH. EACH CYCLE PROFILE 90-55-20 AMPS, WITH 20-MINUTE DWELL EACH LOAD. DEPLETE AT 20 AMP TO 2.0 VDC. CURRENT DENSITY 11.05 MA/SQ.CM. @ 90 AMPS.
-S/N 001	PLACED ON 4.0" DIAMETER COPPER BLOCK WHICH WAS PLACED ON LARGE SLAB OF STEEL. CELL TO COPPER INTERFACE WITH THERMAL GREASE. ROOM AMBIENT CONDITION
-S/N 002	PLACED ON A PIECE OF WOOD. ROOM AMBIENT CONDITIONS.
-S/N 003	UNIQUE CELL (CURRENT DENSITY 11.67 MA/SQ.CM. @ 90 AMPS). PLACED ON A PIECE OF WOOD. ROOM AMBIENT CONDITIONS.
-S/N 004	WRAPPED IN STYROFOAM, PLACED IN STYROFOAM BOX, BACKFILLED WITH STYROFOAM "PEANUTS" (SIMULATION OF SPACE HEAT DISSIPATION REQMTS). PERFORMED THREE CYCLES - TEMP HIGH - REPLACED 4TH CYCLE WITH 20 AMP CONSTANT CURRENT.

FIGURE 6. KARDARPA

TECHNICAL INTERCHANGE, LITHIUM BATTERIES

FUNCTIONAL DATA SUMMARY

		AMP-HRS
CAPACITY TO 28 VDC	S/N 001	266
	S/N 002	261
	S/N 003	267
	S/N 004	285
VOLTAGE REGULATION	ACCEPTABLE	
DISCHARGE RATE	ACCEPTABLE BY TEST DEMONSTRATION	

FIGURE 7. KARDARPA

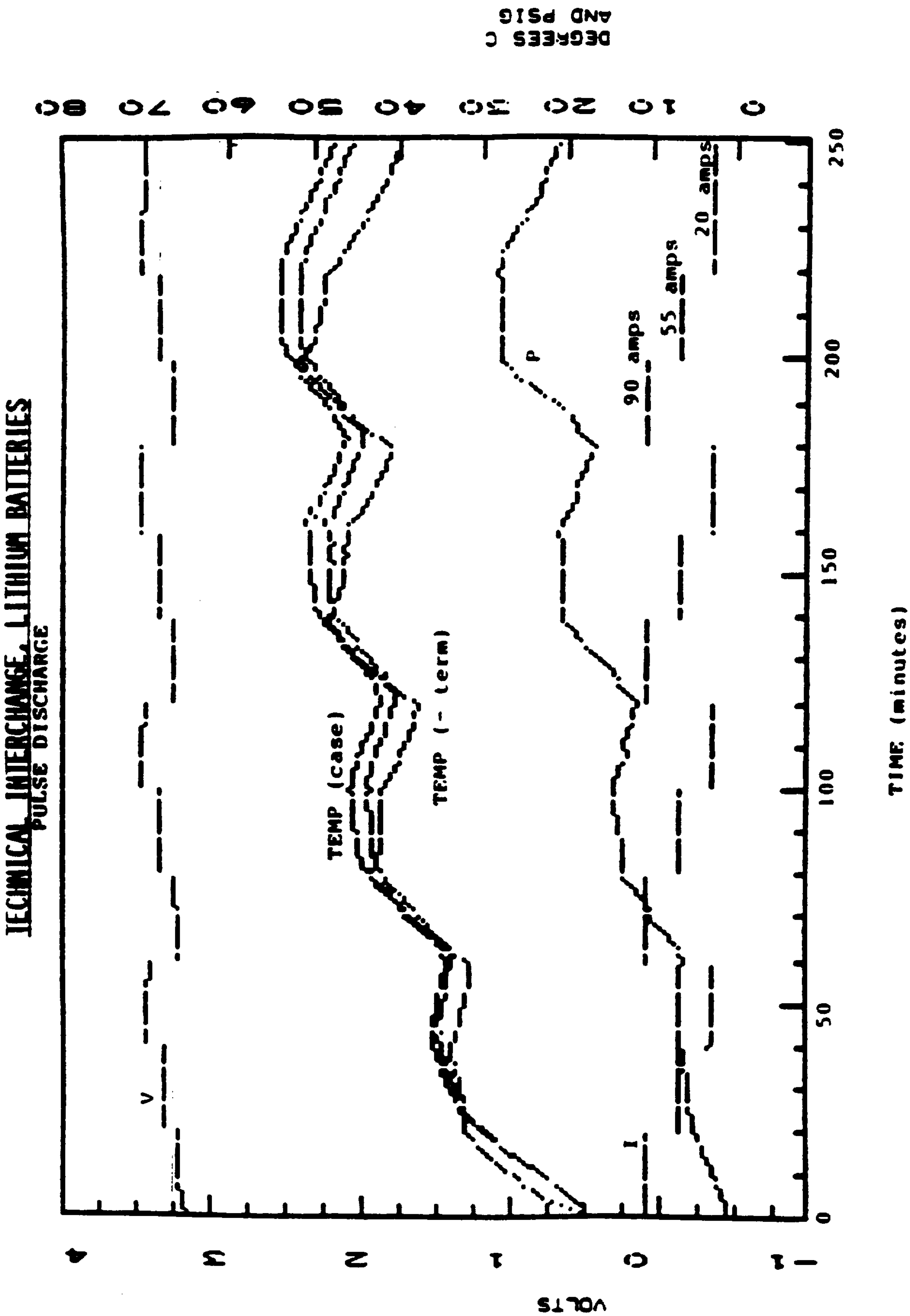


FIGURE 8. KARDARPA

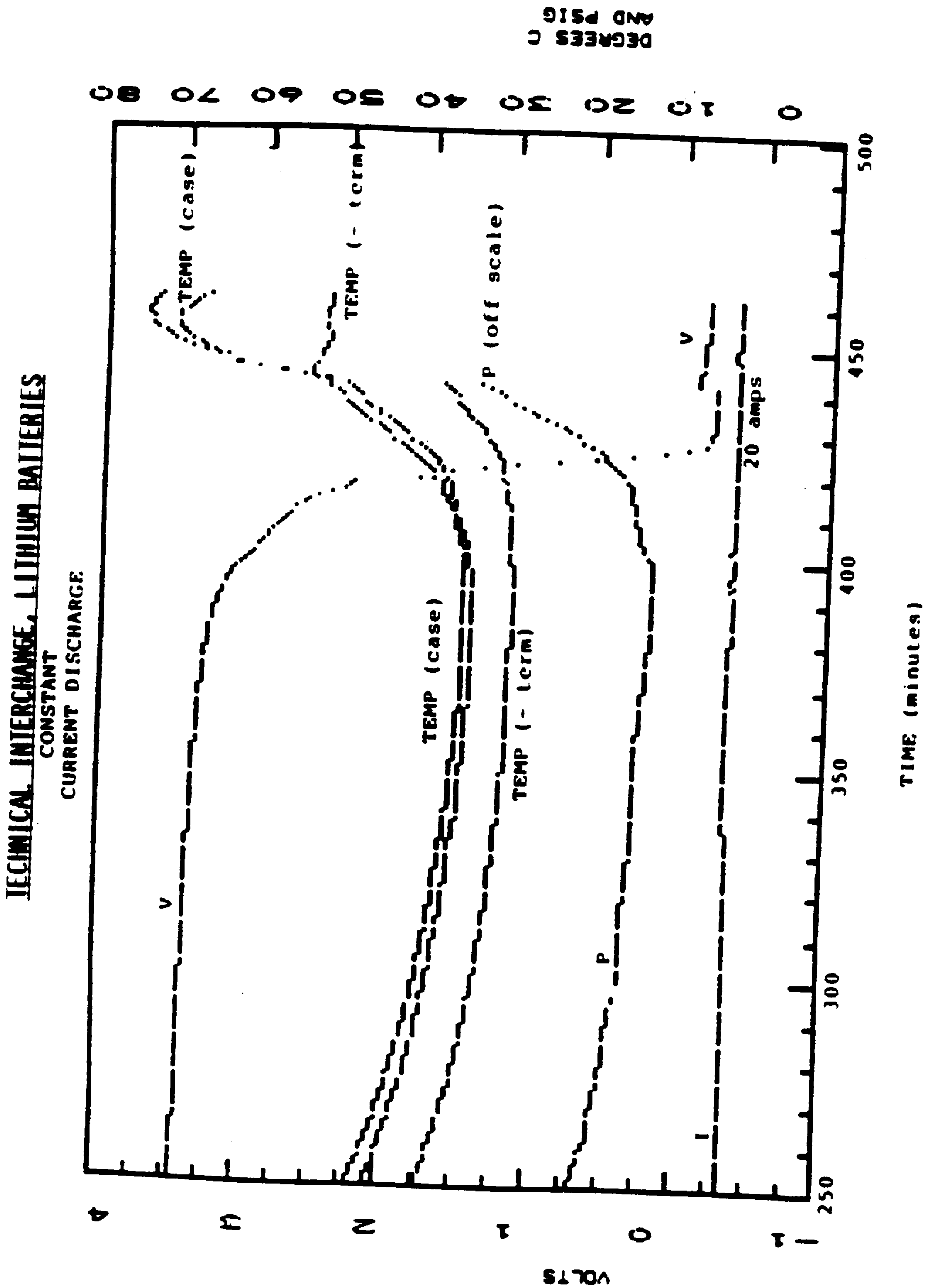


FIGURE 9. KARDARPA

GENERAL DYNAMICS
Space Systems Division

CONCLUSIONS

(250 AH LITHIUM/THIONYL CHLORIDE CELL DEVELOPMENT)

1. CELL DESIGN WITH CYLINDRICAL CONFIGURATION CAN BE BUILT FOR HIGH CAPACITY AND HIGH RATE
2. CELLS OPERATED SAFELY TO LOAD PROFILE (90 AMP. MAXIMUM RATE) FOR 2.5 HOURS IN ADIABATIC ENVIRONMENT
3. SIMPLE THERMAL MODEL USED CAN ACCURATELY PREDICT THE CELL TEMPERATURE DURING CELL DISCHARGE
4. RESULTS CLEARLY ILLUSTRATE THE FEASIBILITY OF LITHIUM/THIONYL CHLORDIE CELLS FOR CENTAUR APPLICATION

FIGURE 10. KARDARPA

9-CELL BATTERY PACKAGING

(CENTAUR BATTERY)

FIGURE 11. KARDARPA

GENERAL DYNAMICS
Space Systems Division

CELL DESIGN

(CENTAUR BATTERY)

- NO CHANGE TO ELECTROCHEMICAL CONFIGURATION
  - -CATHODE TOTAL SURFACE AREA FIXED
  - -LITHIUM ANODE THICKNESS FIXED
  - -CARBON CATHODE WEIGHT FIXED

- CHANGE CELL ASPECT RATIO TO FIT AVAILABLE VOLUME

- OPTIMIZE CONTAINER WALL THICKNESS

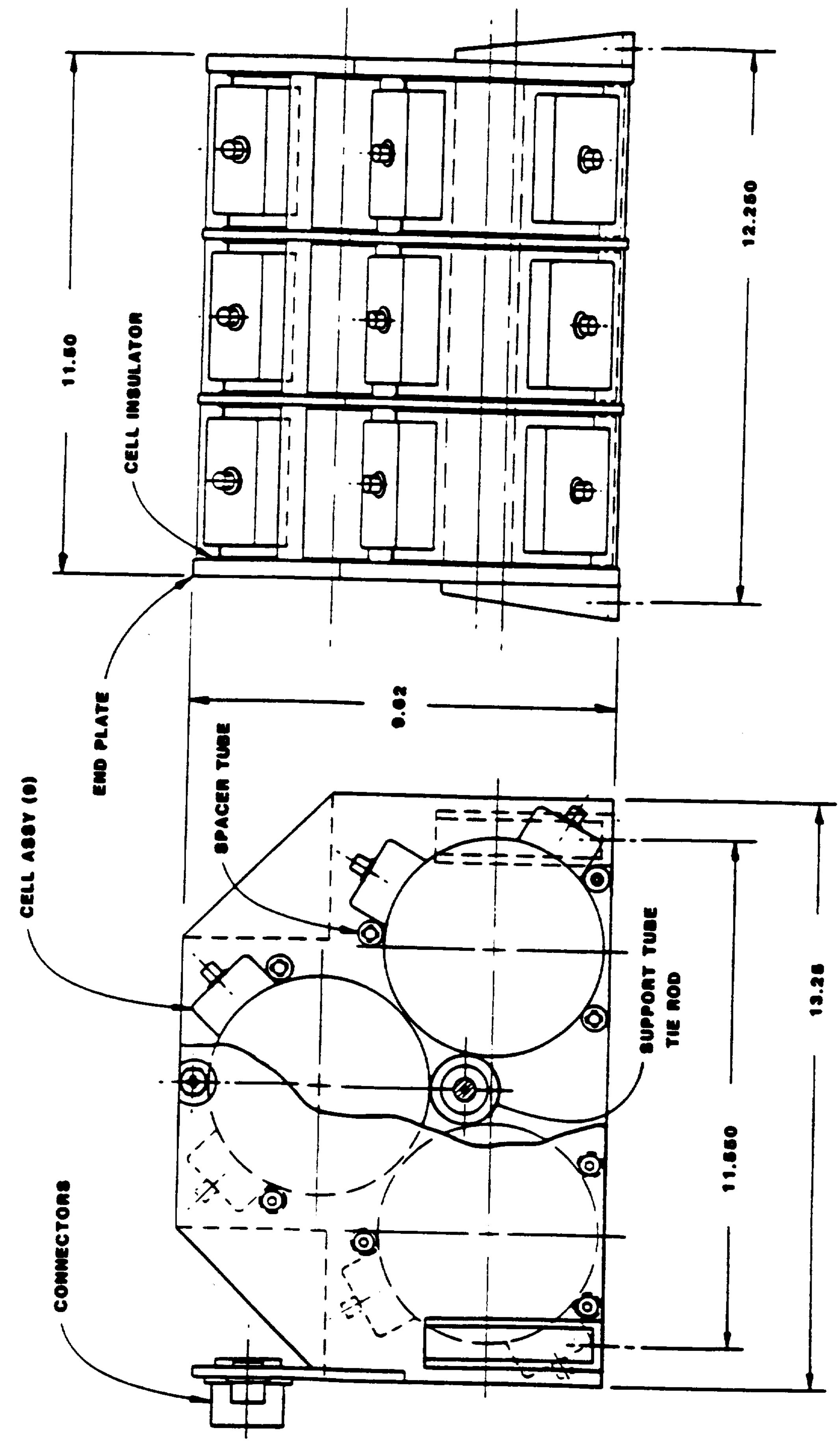
FIGURE 12. KARDARPA

FINAL BATTERY CONFIGURATION

(LITHIUM/THIONYL CHLORIDE CENTAUR BATTERY)

- ARRANGE THE NINE CELLS IN THREE GROUPS: CENTERLINE OF EACH GROUP LOCATED AT THE CORNERS OF AN ISOSCELES TRIANGLE WITH THE BASE PARALLEL TO THE MOUNTING PLANE.
- THE CELLS ARE PRELOADED BY TIE RODS JOINING THE TWO MOUNTING PLATES
- THE CELLS IN EACH GROUP ARE SEPARATED FROM EACH OTHER AND FROM THE END PLATES BY INSULATION

FIGURE 13. KARDARPA



BATTERY CONCEPT

FIGURE 14. KARDARPA

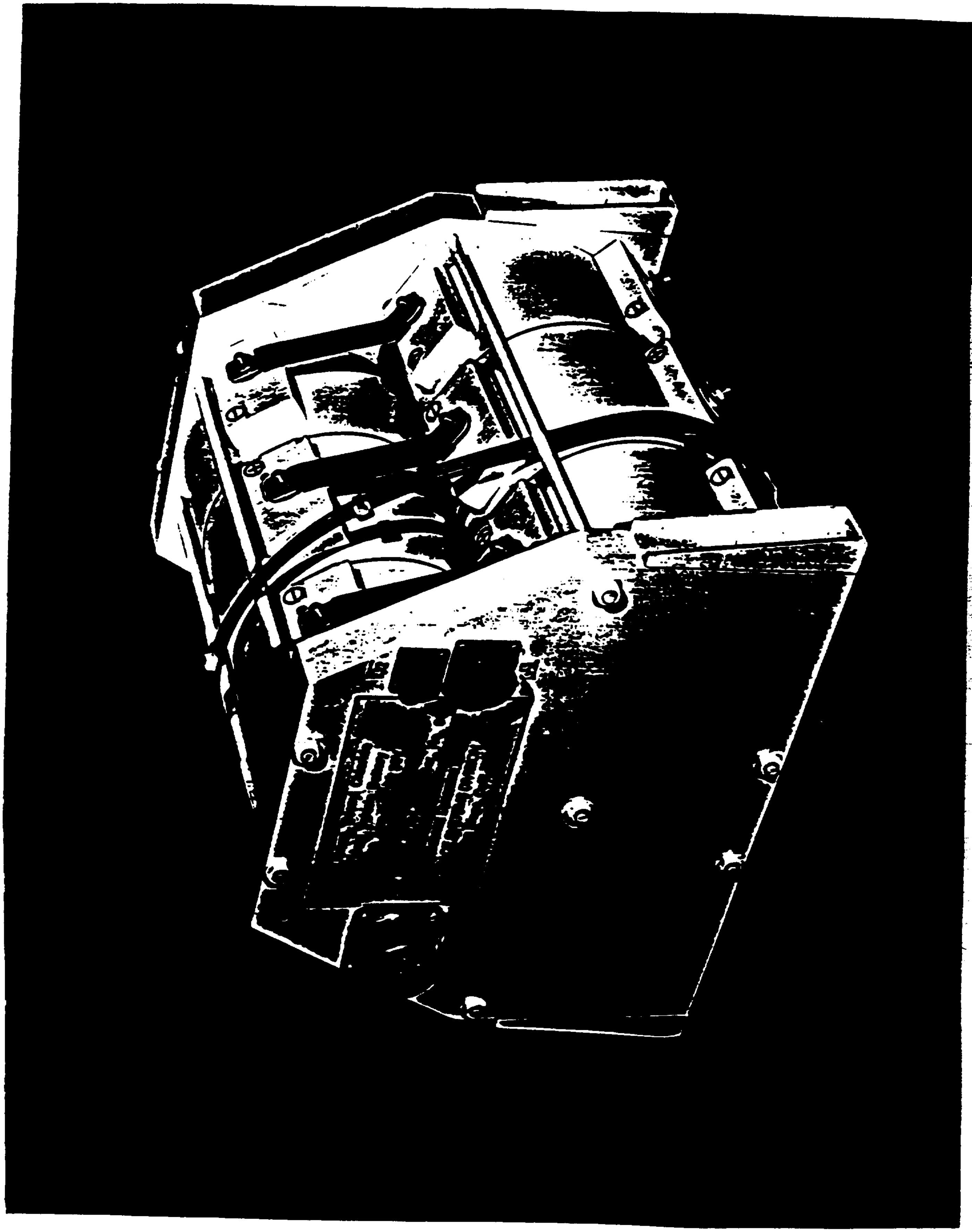
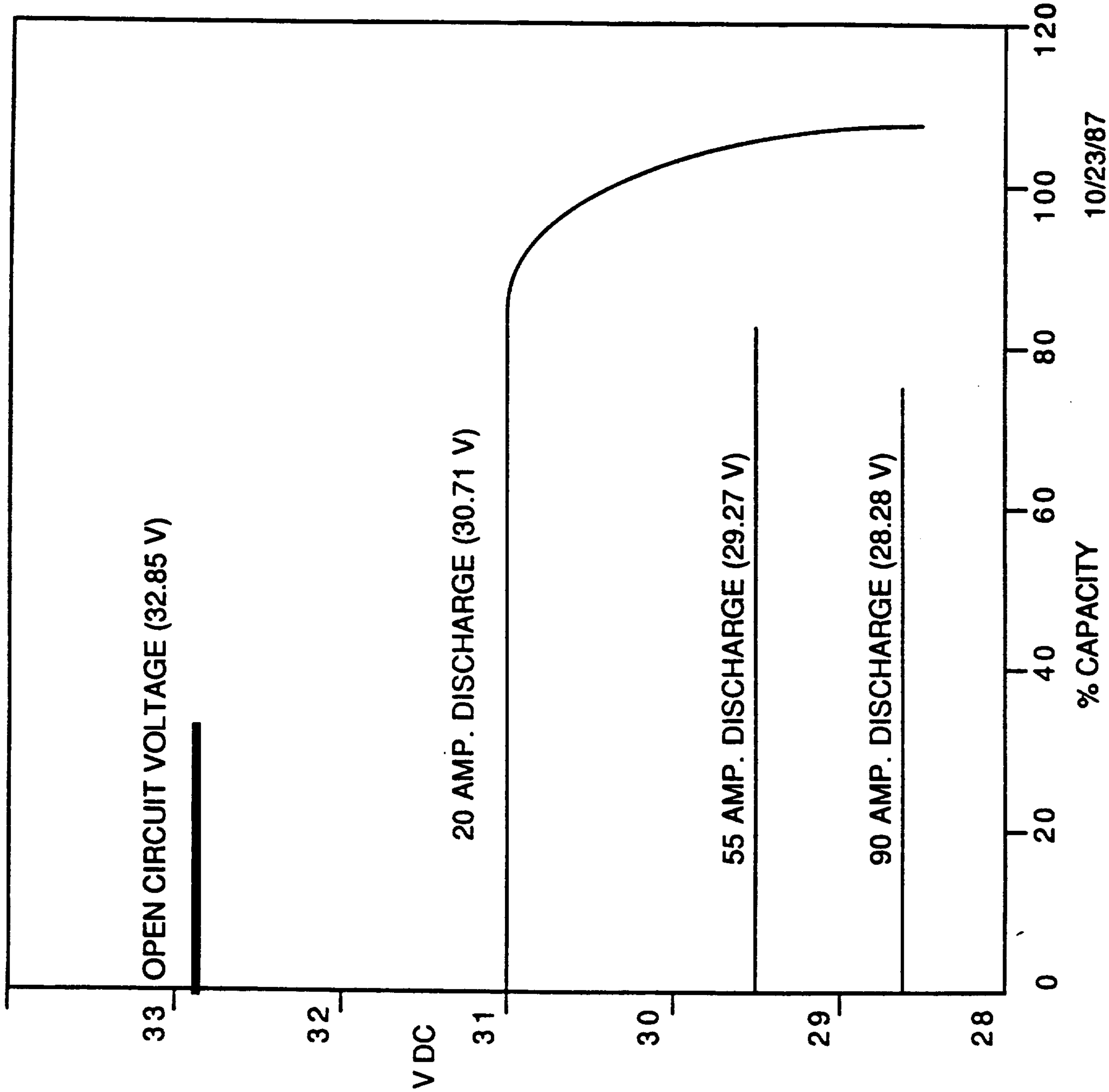


FIGURE 15. KARDARPA

9-CELL LITHIUM BATTERY CHARACTERISTICS
(BASED ON CELL TEST DATA)



THERMAL ANALYSIS MODEL
(Li/SOCl2 BATTERY)

1. HEAT INPUTS TO THE BATTERY
   A. HEAT GENERATION BY POLARIZATION OF CELLS
   B. HEAT GENERATION BY ENTROPY EFFECTS
   C. SPACE HEATING BY SOLAR RADIATION
   D. SPACE HEATING BY EARTH THERMAL RADIATION
2. HEAT OUPUT FROM THE BATTERY
   A. RADIATION HEAT TRANSFER
   B. MINOR CONDUCTION THROUGH MOUNTING FEET
3. HEAT ACCUMULATION IN THE BATTERY
   BATTERY TEMPERATURE INCREASE

GENERAL DYNAMICS
Space Systems Division

FIGURE 17. KARDARPA

HEAT INPUTS TO THE BATTERY (Li/SOCl2 BATTERY)

1. POLARIZATION DEPENDS UPON
   - A. THERMONEUTRAL VOLTAGE (ASSUMED 3.74 V)
   - B. DISCHARGE CURRENT
   - C. INTERNAL RESISTANCE
   - D. TEMPERATURE
   - E. TERMINAL VOLTAGE
2. ENTROPY EFFECTS DEPEND UPON
   - A. INTERNAL SELF-DISCHARGE CURRENT
   - B. DISCHARGE CURRENT
   - C. TEMPERATURE
3. SOLAR AND EARTH RADIATION HEATING DEPENDS UPON
   - A. EXPOSED SURFACE AREA
   - B. EMISSIVITY AND ABSORPTIVITY OF EXPOSED AREA

GENERAL DYNAMICS
Space Systems Division

FIGURE 18. KARDARPA

VARIOUS THERMAL MODEL RUNS
(Li/SOCl2 BATTERY)

1. WORST CASE COLD ENVIRONMENT
2. WORST CASE HOT ENVIRONMENT
3. MEDIUM CURRENT PROFILE, COLD
4. MEDIUM CURRENT PROFILE, HOT

GENERAL DYNAMICS
Space Systems Division

FIGURE 19. KARDARPA

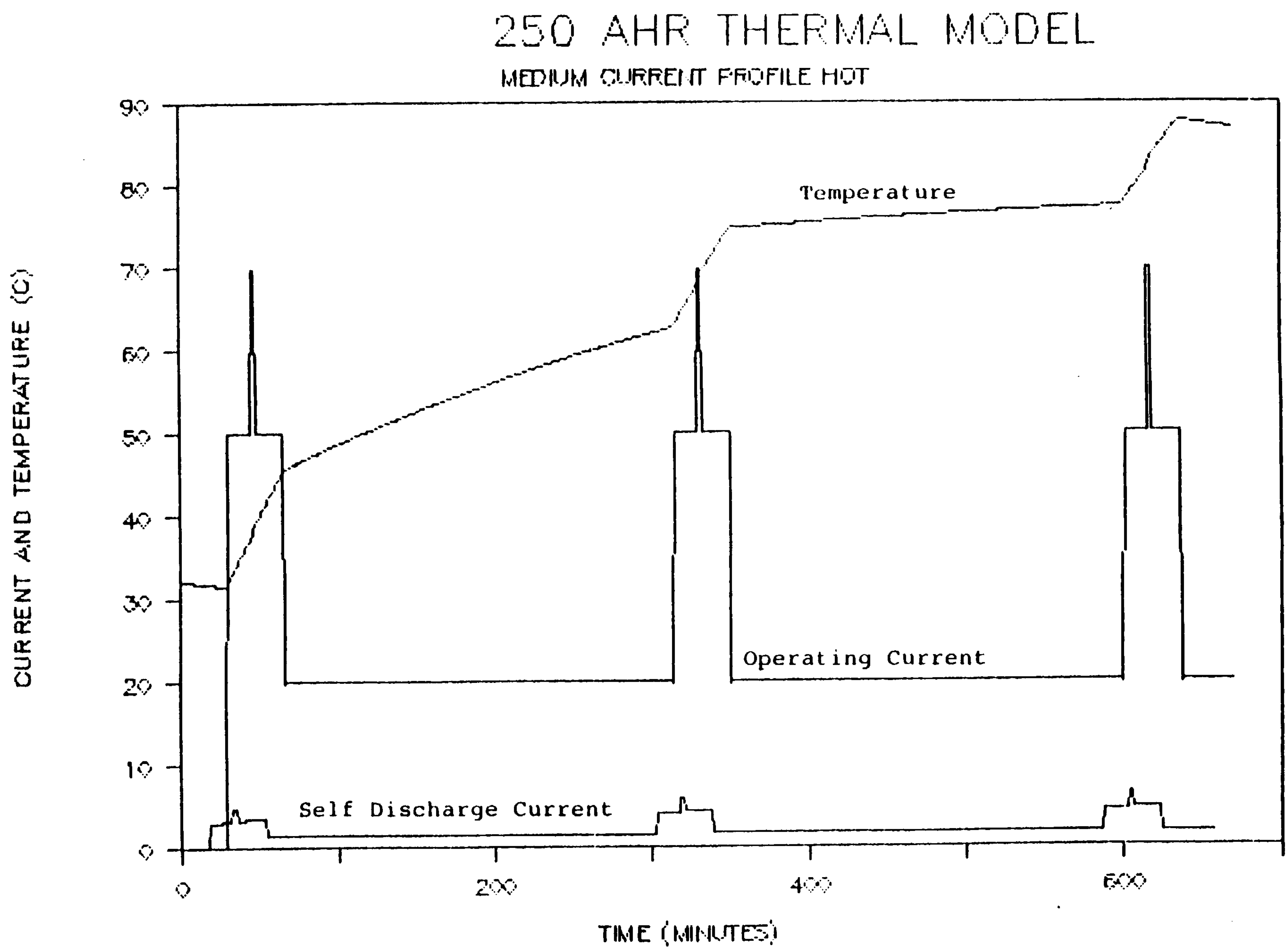


FIGURE 20. KARDARPA

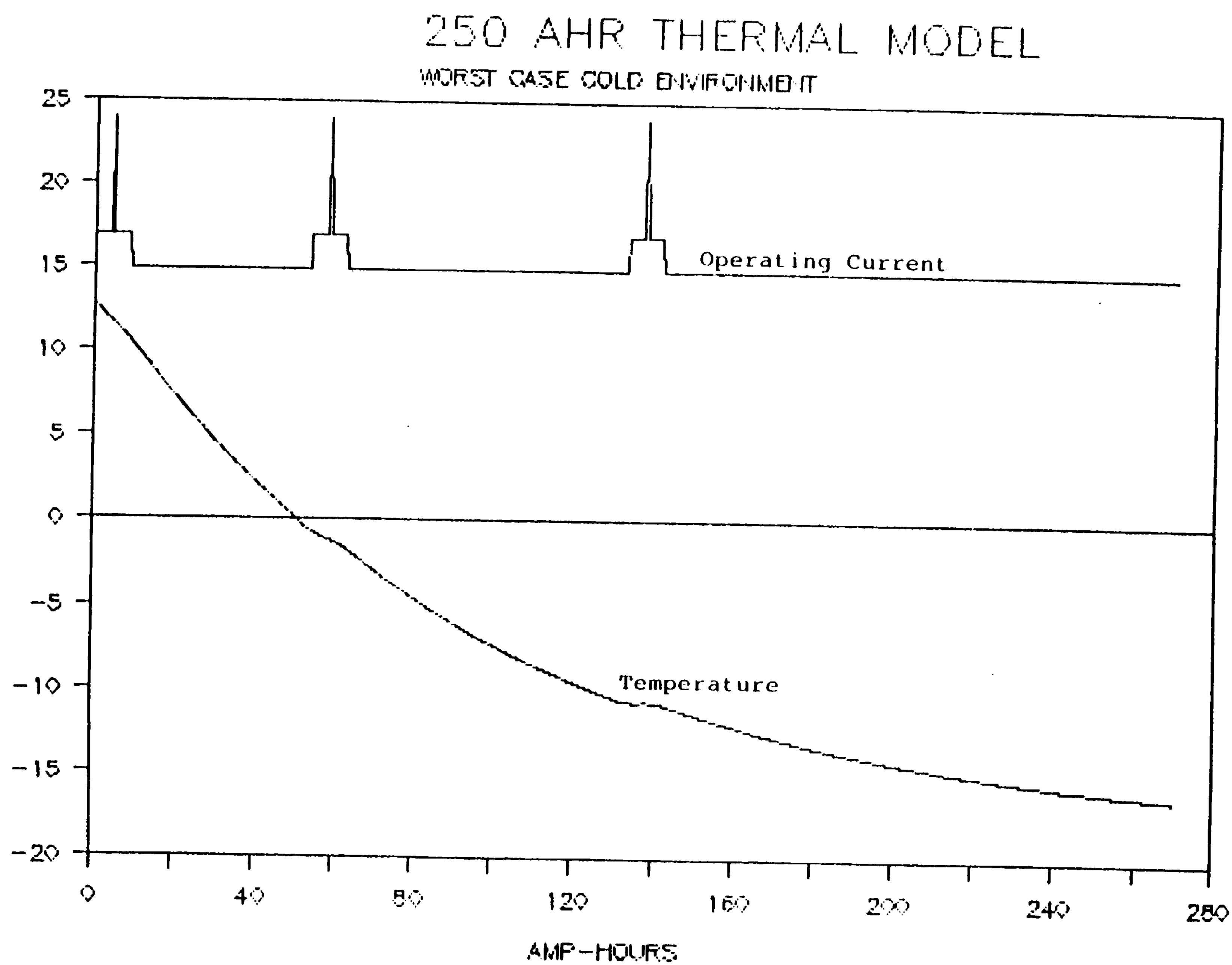


FIGURE 21. KARDARPA

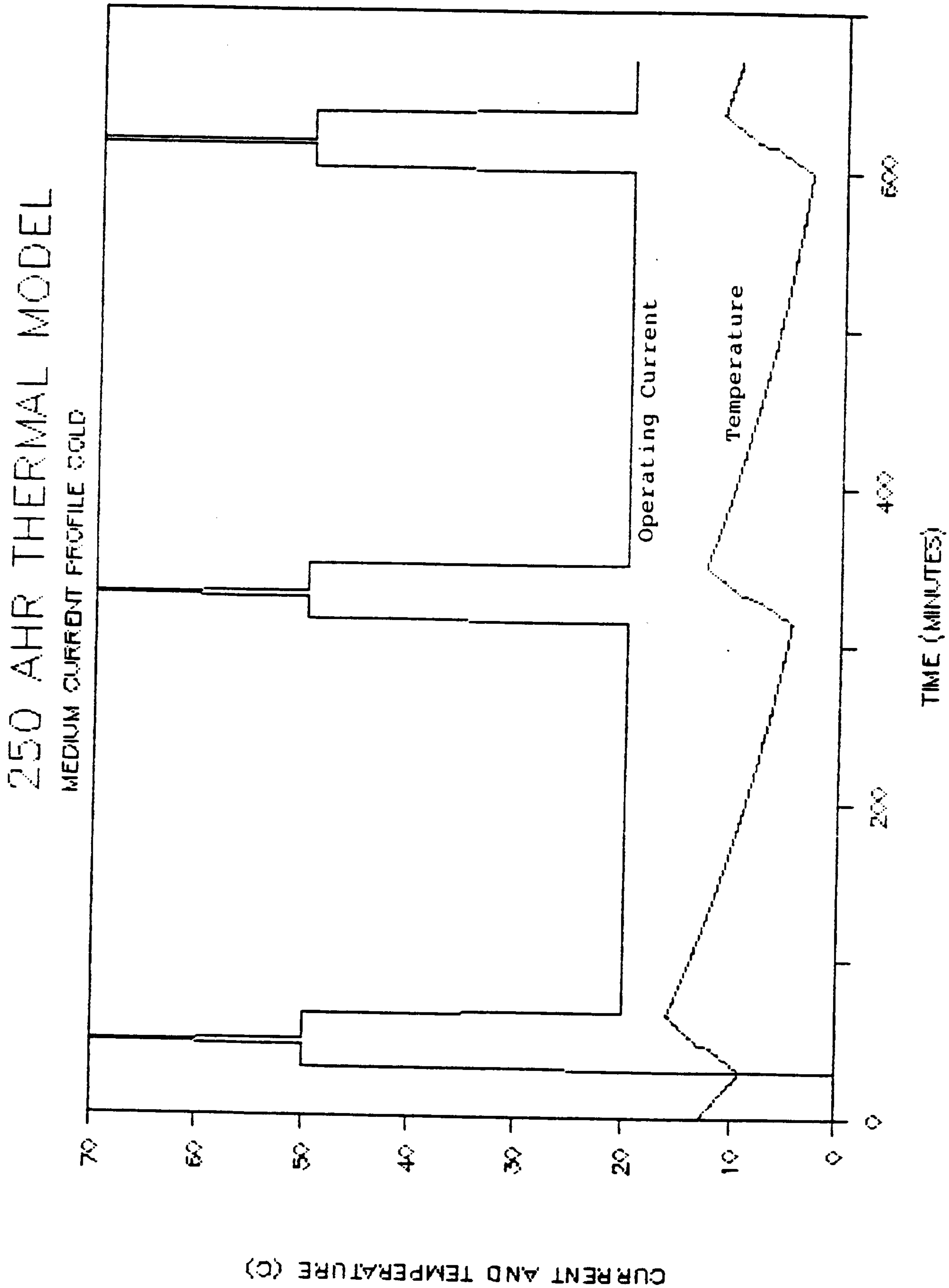


FIGURE 22. KARDARPA

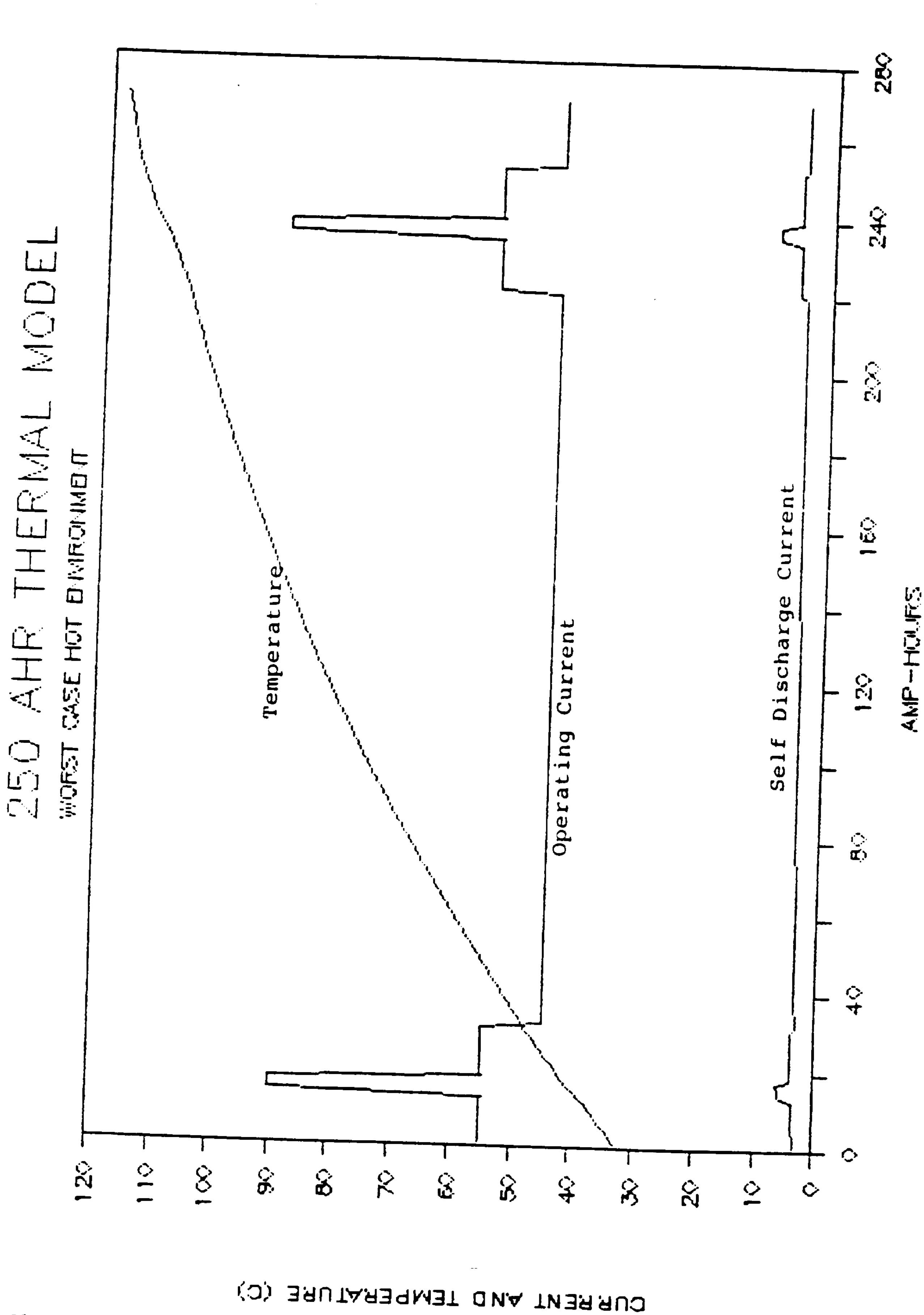


FIGURE 23. KARDARPA

GENERAL DYNAMICS
Space Systems Division

TECHNICAL RISKS

- NO TECHNICAL RISKS IN ELECTROCHEMISTRY OF CELLS
- LOW RISKS IN BATTERY PACKAGING CONCEPT
  (NEED TO VERIFY SHOCK & VIBRATION EFFECTS)

FIGURE 24. KARDARPA

"PERFORMANCE CHARACTERISTICS OF RECHARGEABLE LITHIUM CELLS"

RAO SUBBARAO

Gerald Halpert (JPL) gave the presentation "The Performance Characteristics of Rechargeable $LiMoS_2$ Cells." This talk was originally scheduled to be given by Rao Subbarao (JPL) on JPL's determination of the performance and safety characteristics of secondary lithium cells, specifically the Moli Energy Ltd $LiMoS_2$ cells.

JPL is developing ambient temperature secondary lithium cells for future NASA missions by first establishing a performance and safety data database for various secondary lithium cells currently under development, e.g., JPL, Bell, EIC, and Moli.

JPL has obtained C size $LiMoS_2$ cells from Moli Energy, and has evaluated the cycle life characteristics at various discharge rates (C/10, C/5, and C/2) and at 50% and 100% DOD. The self discharge properties of these cells were also examined before and after cycling. The safety characteristics were considered including short circuit, overcharge and overdischarge scenarios.

The data shows that C/5 discharge rate showed the most number of cycle compared to other two rates when cycled at 100% DOD. The summary of the tests are:

Initial Capacity (to 1.3V)

C/10	2.2 AH
C/5	2.1 AH
C/2	1.7 AH

Cycle Life (100% DOD)

C/10	70
C/5	260
C/2	125

For the short circuit test, both fresh and cycled cells were short circuited ($R \leq 0.1\ \Omega$) in fully charged condition. The cell current reached a peak of 2.3A after 300 minutes, while the cell temperature peaked around 130 degrees F from ambient 70 degrees F after 310 minutes. For the overcharge test, fully charged, cycled cells were under forced overcharge at 1.25A for 12 hours. The cell temperature increased from 70 degrees F at the start to 158 degrees F after 3 hours. There was no venting of the cell.

And for the overdischarge test, fully discharged cycles were under forced discharge at 1.25A for 12 hours. The cell went into negative voltage after 5 hours of discharge, and eventually vented after 12 hours of discharge.

In summary, the JPL work has shown $LiMoS_2$ cells have limited cycle life capability, is relatively safe, and that cycle life of cells at the C/10 discharge rate is less than at the C/5 and C/2 rates. Another surprising observation is that the cycle life performance of cells at 50% DOD is inferior to 100% DOD.

Q. Andrasik (NASA Lewis): Have you measured the coulombic efficiency under surge and how long did they stay on open circuit after discharge and before discharge?

A. Yes; there was a relatively short time between charge and discharge.

A. Timmerman (JPL): Cells were discharged simultaneously with the highest DOD--they varied between ???

Q. Sulkes (USALABWM): Did you do conditioning in the 50 percent DOD?

A. No.

Q. Francis (Aerospace Corp.): Are you able to recover any of the fading capacity? (Rao would know.)

A. No. It wasn't done.

Q. Margalit (Tracor): What is the mode of discharge?

A. There is a phase shift in the sulfide. You recover by discharging down to the lower voltage.

PERFORMANCE AND SAFETY CHARACTERISTICS
OF Li/MoS2 CELLS

JPL

F. DELIGIANNIS, J. TARASZKIEWICZ, S. SUBBARAO, G. HALPERT

FIGURE 1. SUBBARAO

OBJECTIVE

DETERMINE THE PERFORMANCE AND SAFETY CHARACTERISTICS OF SECONDARY LITHIUM CELLS

FIGURE 2. SUBBARAO

BACKGROUND

- JPL IS DEVELOPING AMBIENT TEMPERATURE SECONDARY LITHIUM CELLS FOR FUTURE NASA MISSIONS.

- TO ASSESS THE PRESENT STATE OF THE ART WE ARE ESTABLISHING A PERFORMANCE AND SAFETY DATA BASE FOR VARIOUS SECONDARY LITHIUM CELLS CURRENTLY UNDER DEVELOPEMENT.
  (BELL, EIC, JPL, MOLI)

- THIS PRESENTATION IS CONCERNED WITH THE Li/MoS_2 CELLS OF MOLI ENERGY LTD.

FIGURE 3. SUBBARAO

APPROACH

- O PROCURE 'C' SIZE CELLS FROM MOLI ENERGY LTD.

- O EVALUATE THE CYCLE LIFE CHARACTERISTICS OF Li/MoS_2 CELLS AT VARIOUS:

  - O DISCHARGE RATES (C/10, C/5, C/2)
  - O DEPTH OF DISCHARGES (100%, 50%)

- O EVALUATE SELF DISCHARGE PROPERTIES OF CELLS BEFORE AND AFTER CYCLING.

- O DETERMINE THE SAFETY CHARACTERISTICS OF CELLS UNDER:

  - O SHORTCIRCUIT
  - O OVERCHARGE
  - O OVERDISCHARGE

FIGURE 4. SUBBARAO

CYCLE LIFE TESTING DETAILS

CHARGE

METHOD:	CONSTANT CURRENT
RATE:	C/12.5 (200mA)
C.V:	2.4 V

DISCHARGE

METHOD:	CONSTANT CURRENT
RATE:	C/10 (250mA), C/5 (500mA), C/2 (1.25A)
C.V:	1.3 V

DEPTH OF DISCHARGE: 100%, 50%

TEMPERATURE: AMBIENT

FIGURE 5. SUBBARAO

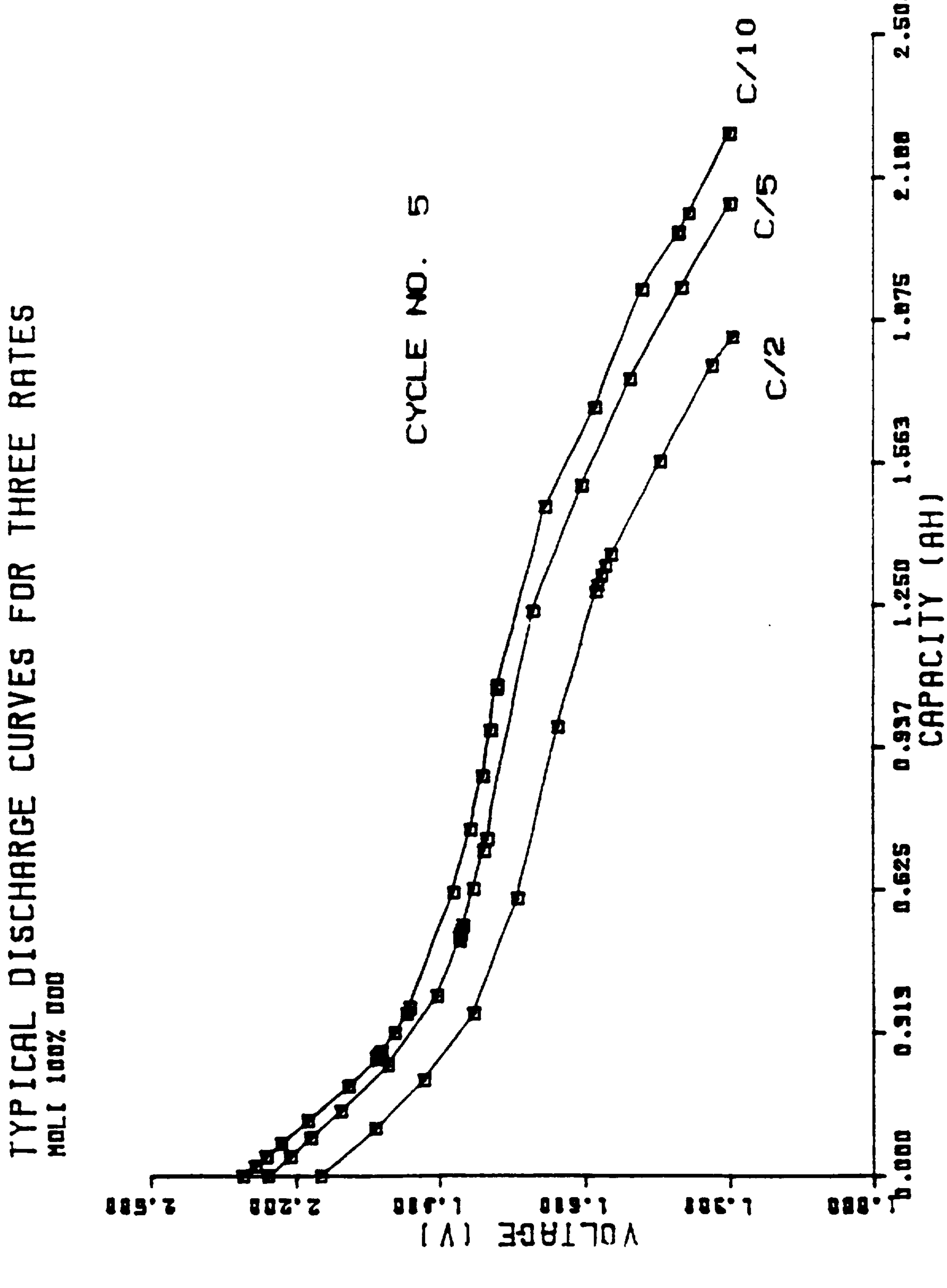


FIGURE 6. SUBBARAO

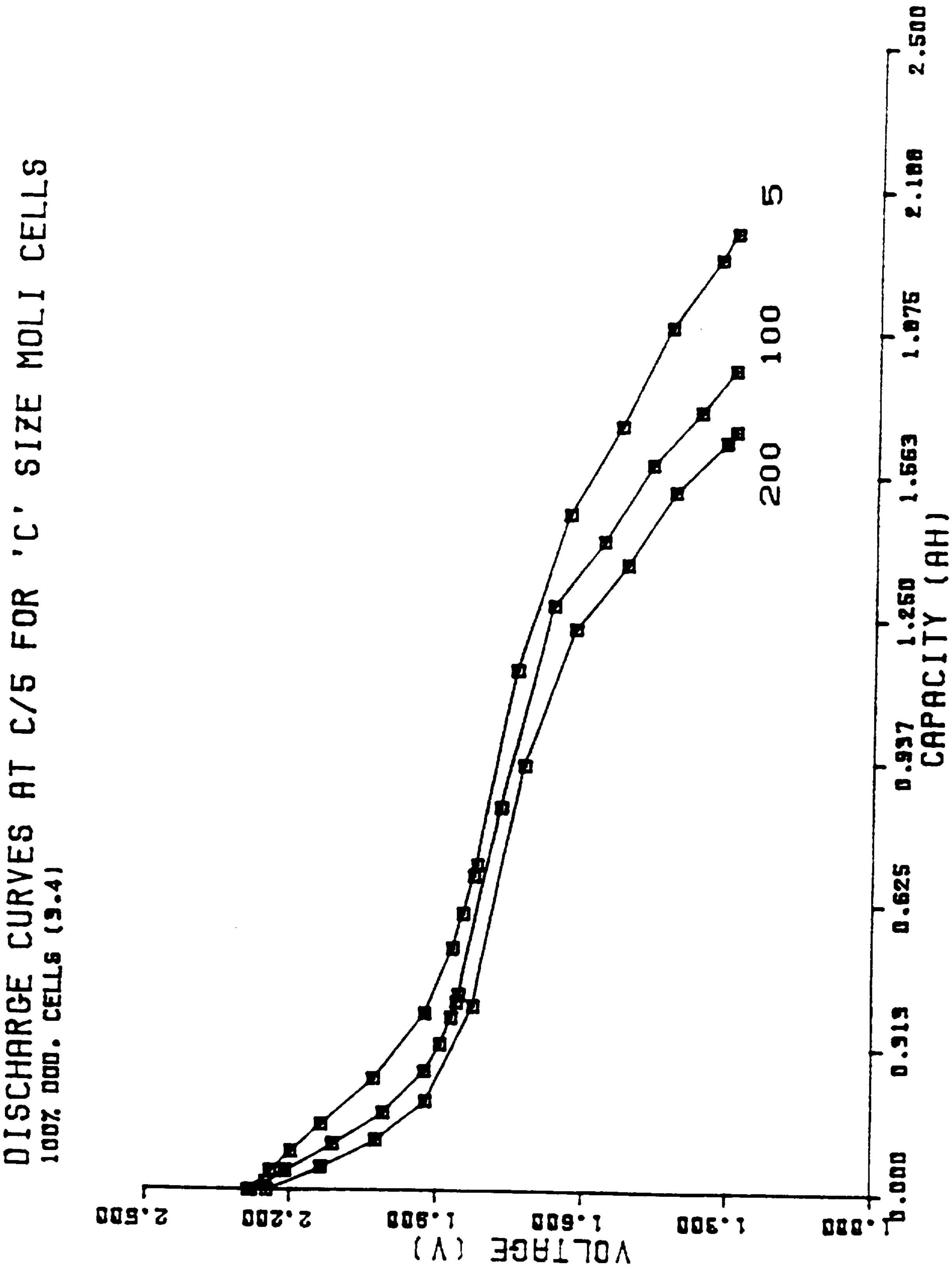


FIGURE 7. SUBBARAO

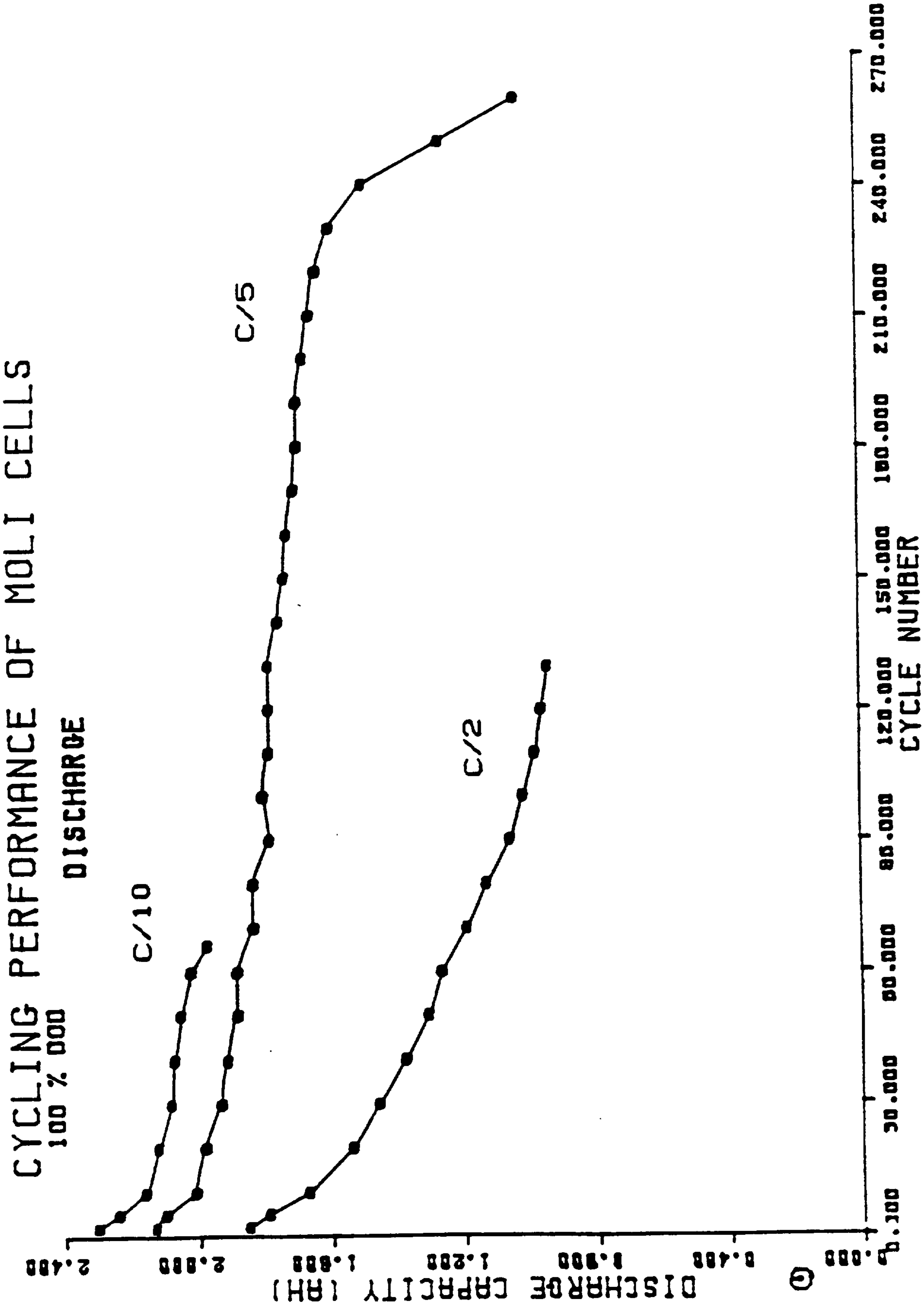


Figure 8. Subbarao

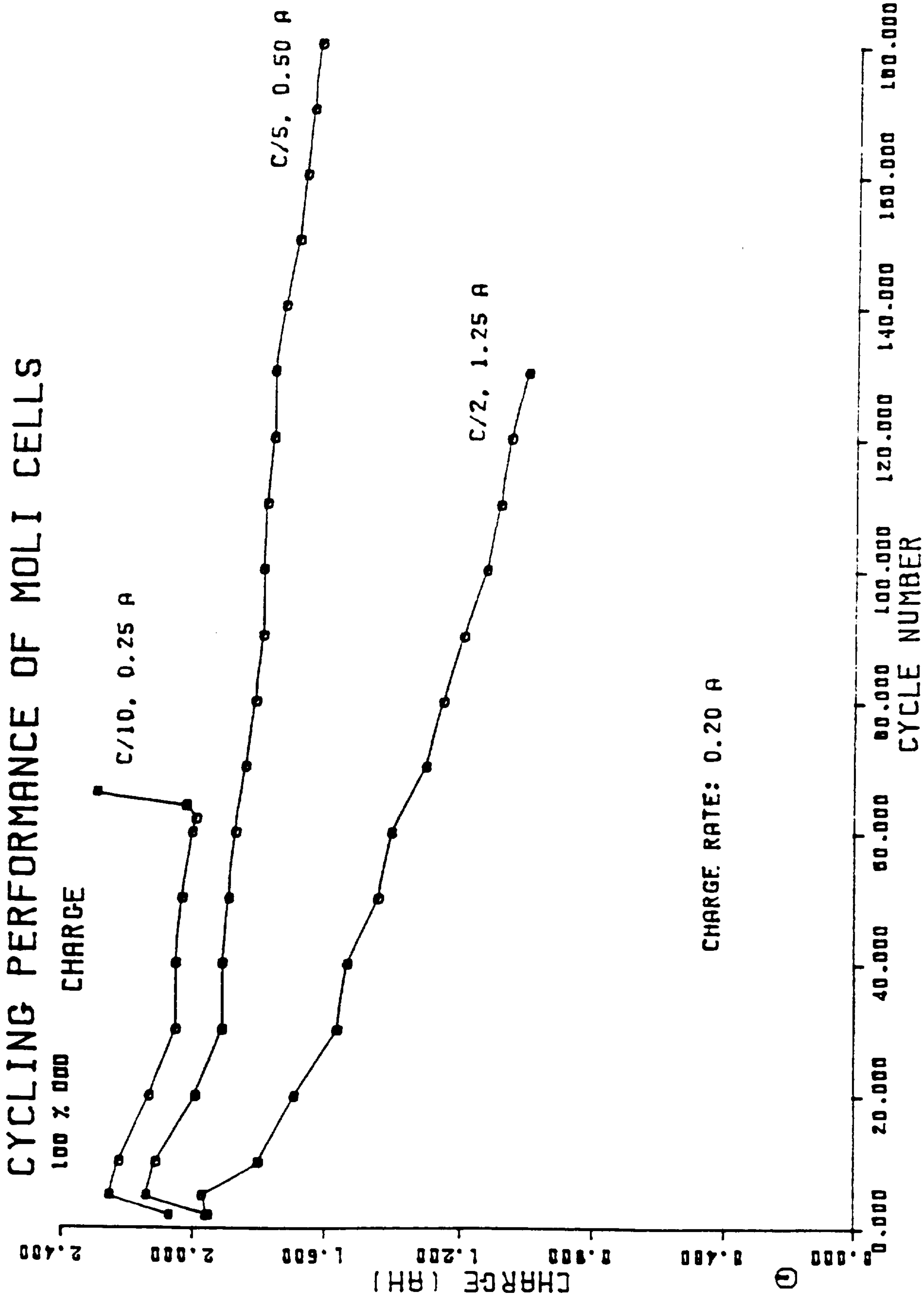


FIGURE 9. SUBBARAO

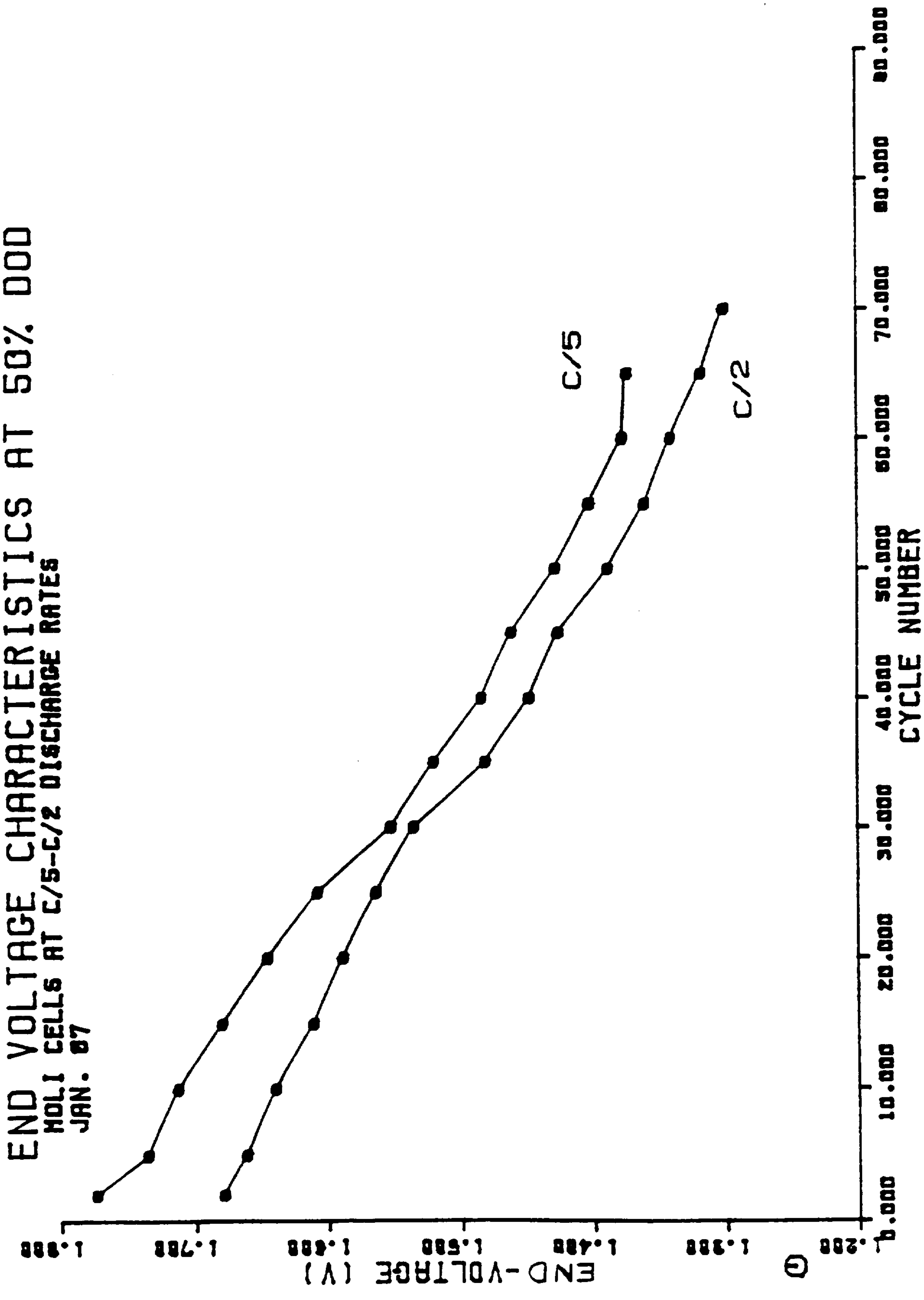


Figure 10. Subbarao

OUTLINE OF SAFETY TESTS

SHORT CIRCUIT: FRESH AND CYCLED CELLS WERE SHORT CIRCUITED ($R<0.1\ \Omega$) IN FULLY CHARGED CONDITION.

OVERCHARGE: FULLY CHARGED CYCLED CELLS WERE FORCED OVER-CHARGED AT 1.25 A FOR 12 HOURS.

OVERDISCHARGE : FULLY DISCHARGED CYCLED CELLS WERE FORCED OVERDISCHARGED AT 1.25 A FOR 12 HOURS.

FIGURE 11. SUBBARAO

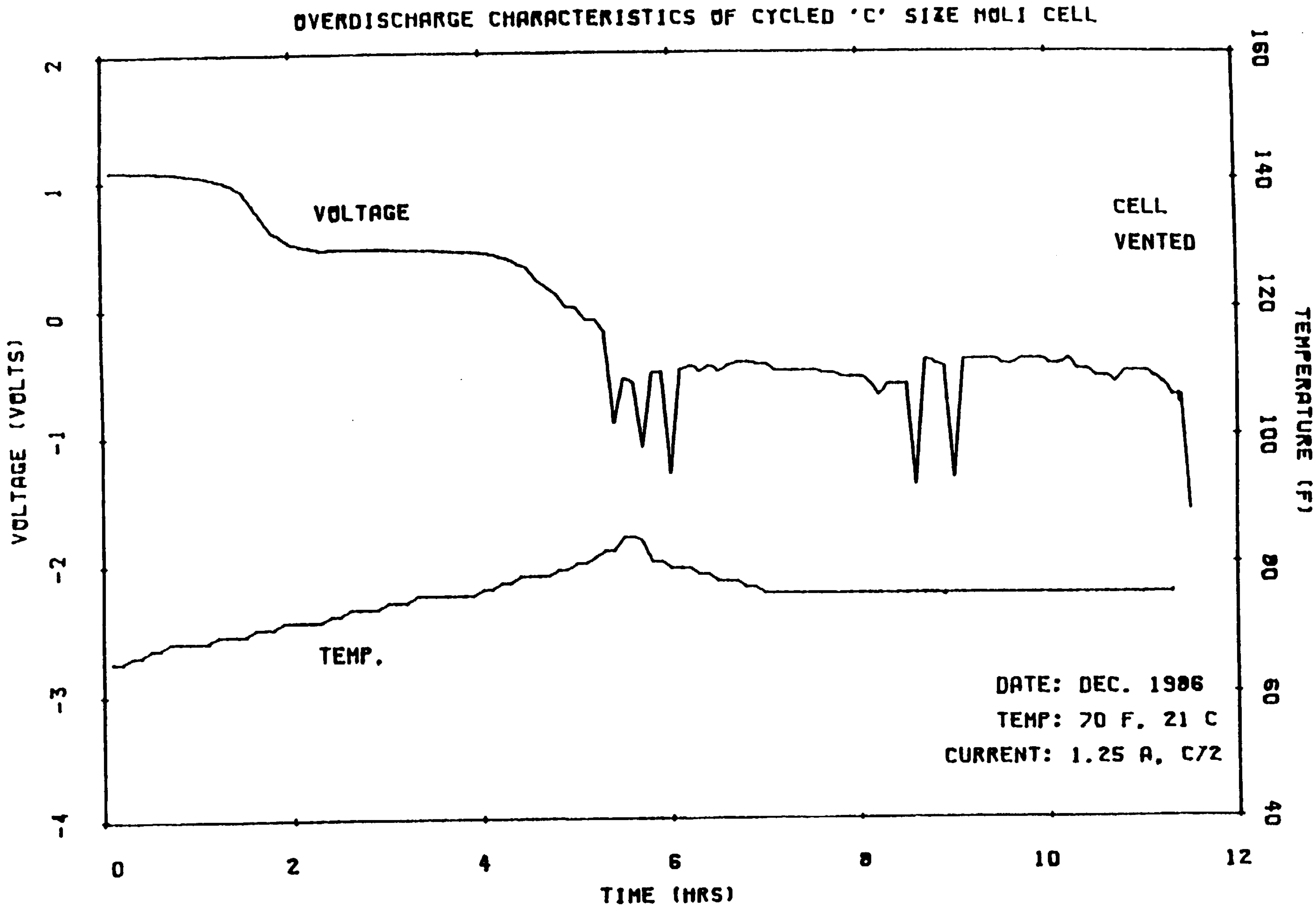


FIGURE 13. SUBBARAO

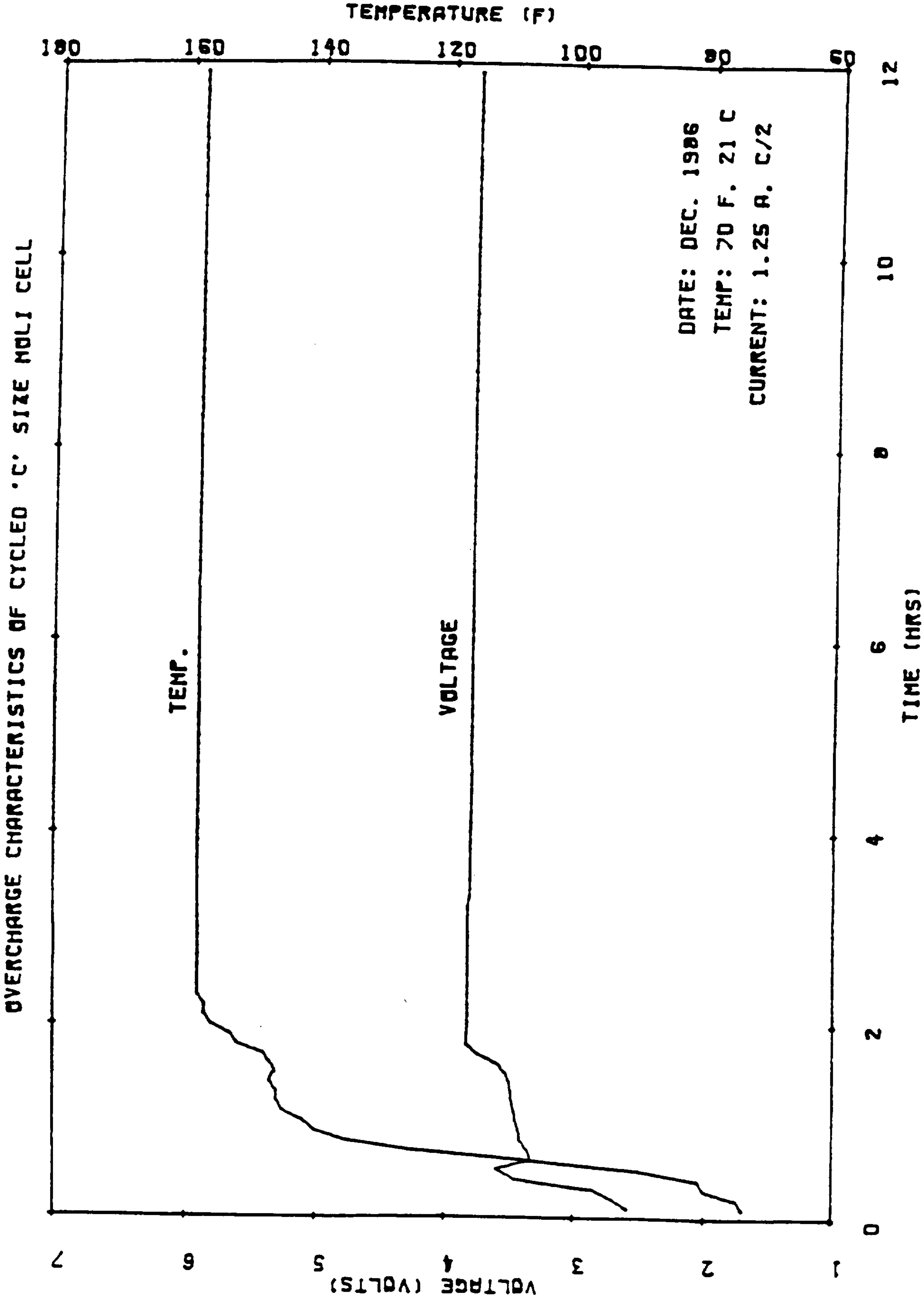


FIGURE 12. SUBBARAO

SHORT CIRCUIT OF FULLY CHARGED FRESH 'C' SIZE MOLI CELL LOAD LESS THAN 0.1 OHM

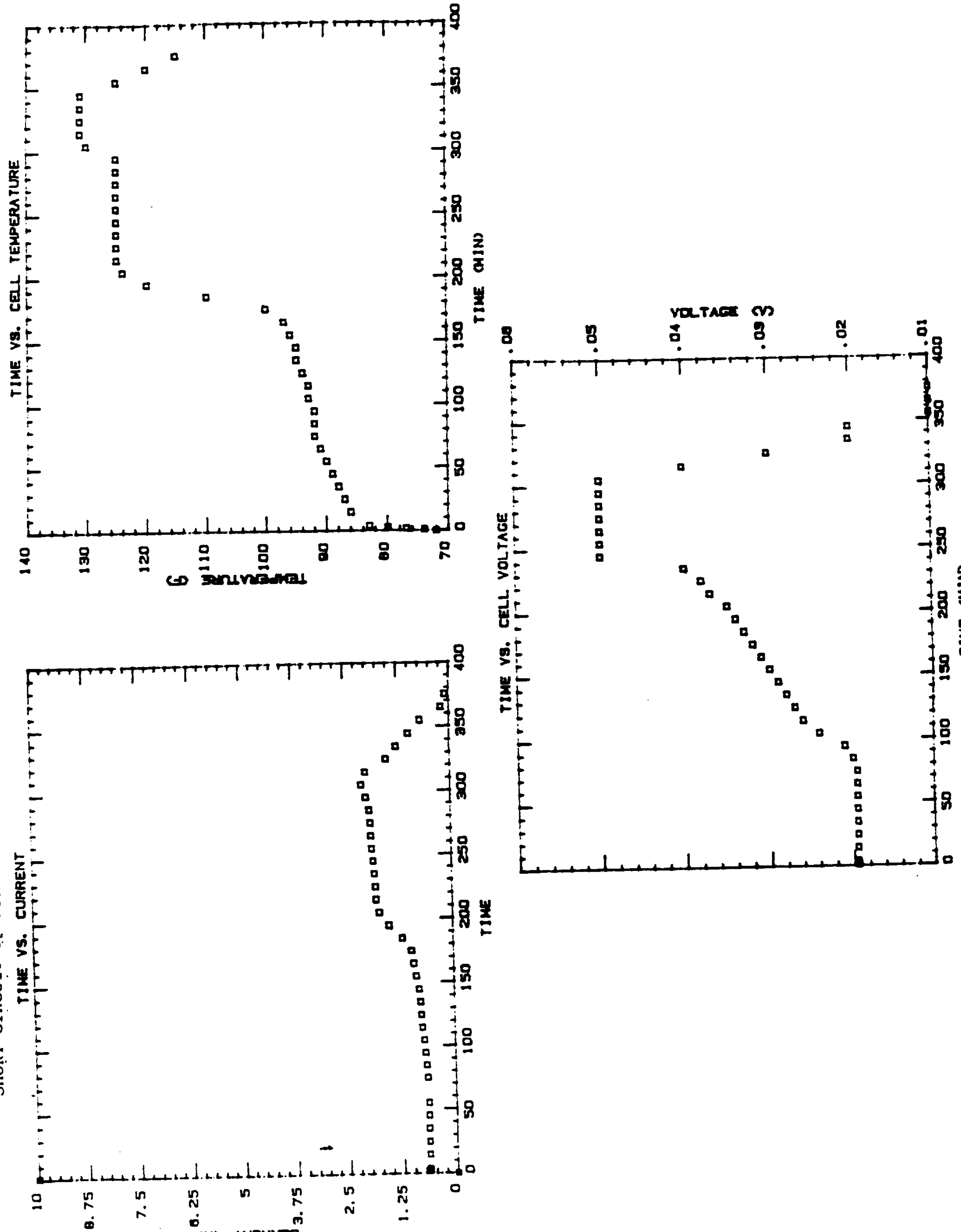


FIGURE 14. SUBBARAO

SUMMARY OF TEST RESULTS

PARAMETER:		
OCV (FULLY CHARGED):		2.3 V
INITIAL CAPACITY (TO 1.3V)		
	C/10	2.2 AH
	C/5	2.1 AH
	C/2	1.7 AH
CYCLE LIFE (100 % DOD)		
	C/10	70
	C/5	260
	C/2	125
WEIGHT:		69 g
ENERGY DENSITY:		
	C/10	54 WH/KG
	C/5	52 WH/KG
	C/2	42 WH/KG

FIGURE 15. SUBBARAO

CONCLUSIONS

- CELLS HAVE LIMITED CYCLE LIFE CAPABILITY.
- CYCLE LIFE OF CELLS AT THE C/10 DISCHARGE RATE IS FAR LESS THAN AT THE C/5 AND C/2 RATES.
- CYCLE LIFE PERFORMANCE OF CELLS AT 50% DOD IS INFERIOR TO 100% DOD.
- CELLS ARE RELATIVELY SAFE.

FIGURE 16. SUBBARAO

SESSION III

NiCd

Chairman: Mr. David Baer, Hughes Aircraft

"POROUS NONSINTERED NICKEL-COATED GRAPHITE (NCG) FIBER ELECTRODE STRUCTURES"

STEVE LIPKA

The first paper of the NiCd session was by Steve Lipka of American Cyanamid on "Porous Nonsintered Nickel-Coated Graphite (NCG) Fiber Electrode Structures." Lipka said that he had given this paper before at an Electrochemical Society Meeting (ECS). He showed photos of nickel-sintered fibers from a competitor and a micrograph from American Cyanamid. There has recently been interest shown in high-porosity structures like these. Making NCG starts with material having 50 percent nickel coating. Dark areas in the photo of the fiber mat, (Lipka [Figure 2]), are the binder. The fibers have many contact points. The processing to prepare NCG fiber mats ends with an additional overplating (Lipka [Figure 4]).

The micrographs show that there are no non-uniformities of the overplated nickel, in the buildup (Lipka [Figure 12]). The group has plated various thicknesses of nickel, and they get metallurgical binding at high thicknesses. Resistivity of NCG drops as coulombs increase, and this demonstrates true metallurgical bonding. Overplating reduces porosity and increases pore diameters.

NCG performance results to date include plating with 100 g/m^2 of nickel and running up to 600 cycles without degradation (Lipka [Figure 13]).

Q. Edwards (Bell Labs.): Were you ever able to vary the paper-making process? Did you reduce the pore size?

A. Yes, we can use smaller and larger graphite fibers--the smallest are about 5 micrometers.

Q. Koehler (FORD): What is the active material loading level?

A. Some results were obtained using electrochemical impregnation; others were done with chemical impregnation using a commercial process. We ran load 1.6g/cc of void.

Q. _____? : What is the tensile strength of plates made this way?

A. We don't know yet. We will be testing. We do know that it gets stronger and more rigid with more and more nickel plating.

NICKEL COATED GRAPHITE FIBER ELECTRODE STRUCTURES

STEPHEN M. LIPKA
AND
DALE E. HALL

AMERICAN CYANAMID COMPANY
CHEMICAL RESEARCH DIVISION
STAMFORD, CT. 06904

R.W. FREEMAN, A.J. SALKIND AND V. VISWANATHAN

RUTGERS UNIVERSITY
DEPARTMENT OF CHEMICAL AND BIOCHEMICAL
ENGINEERING

FIGURE 1. LIPKA

SURFACE [42.6 X]

SURFACE [911 X]

NATIONAL STANDARD FIBREX NICKEL MAT

[0.150 in. thick, 20 μm fiber, 0.92 g/in. ^{2}, 96% porosity]

FIGURE 2. LIPKA

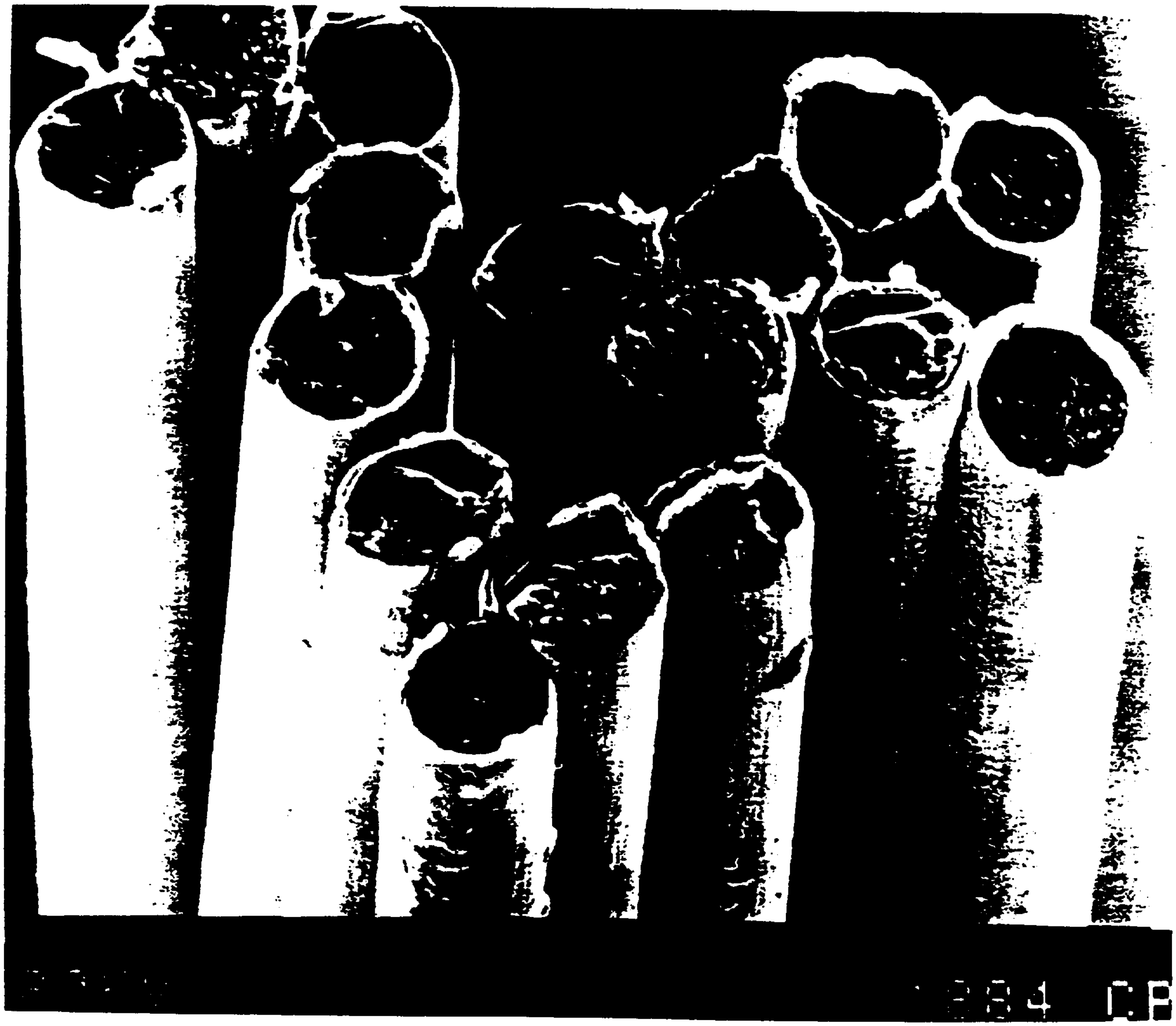


Figure 5. Section of Nickel Coated Graphite Fiber tow showing deposit surface morphology.

FIGURE 3. LIPKA

PROCESSING STEPS FOR PREPARING NCG FIBER MATS

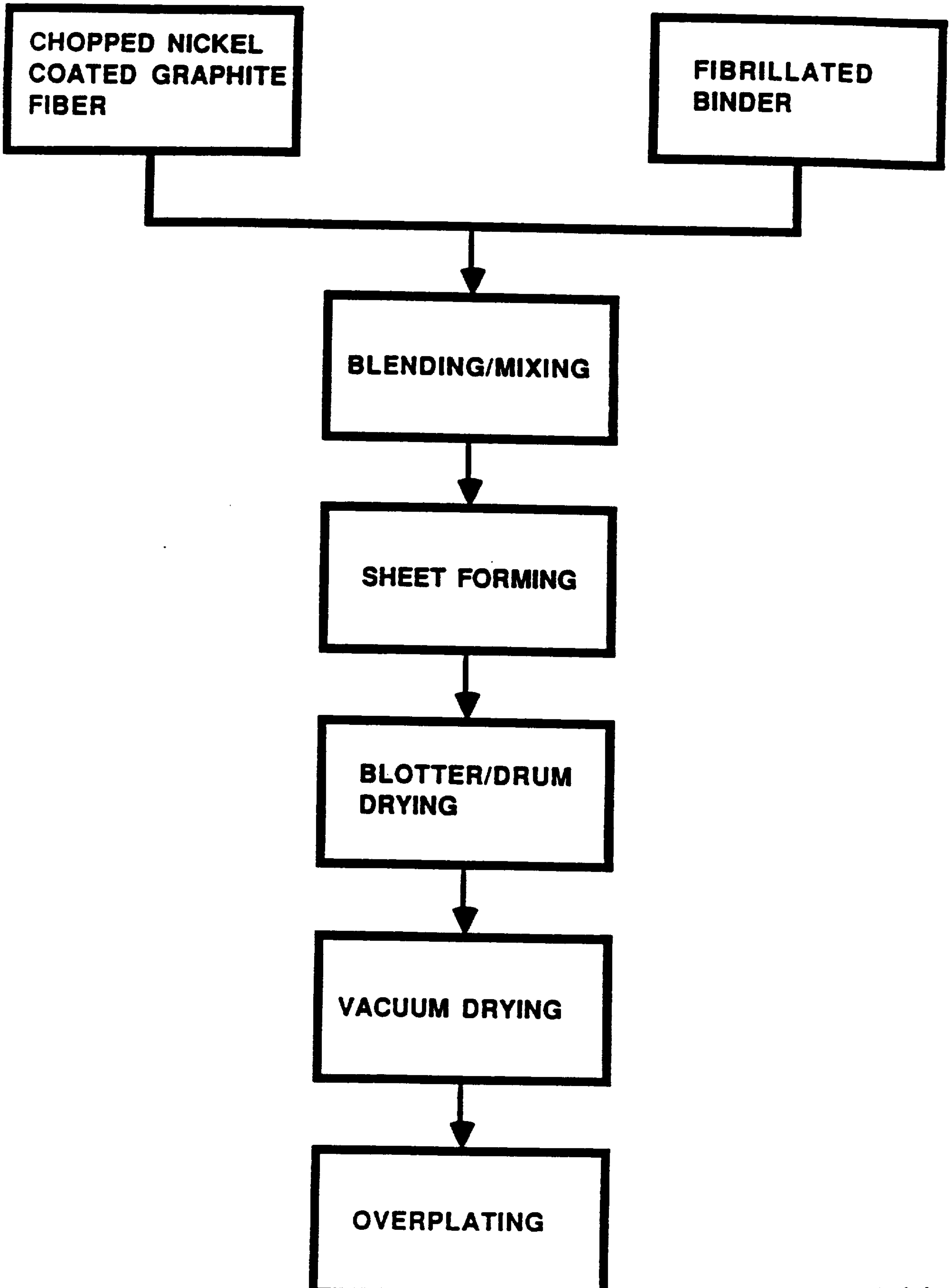


FIGURE 4. LIPKA

SURFACE [1.01 KX]

AS-CAST NICKEL COATED GRAPHITE FIBER MAT,
SHOWING BONDING BY FIBRILLATED BINDER

FIGURE 5. LIPKA

PROCESSING STEPS FOR PREPARING NCG FIBER MATS

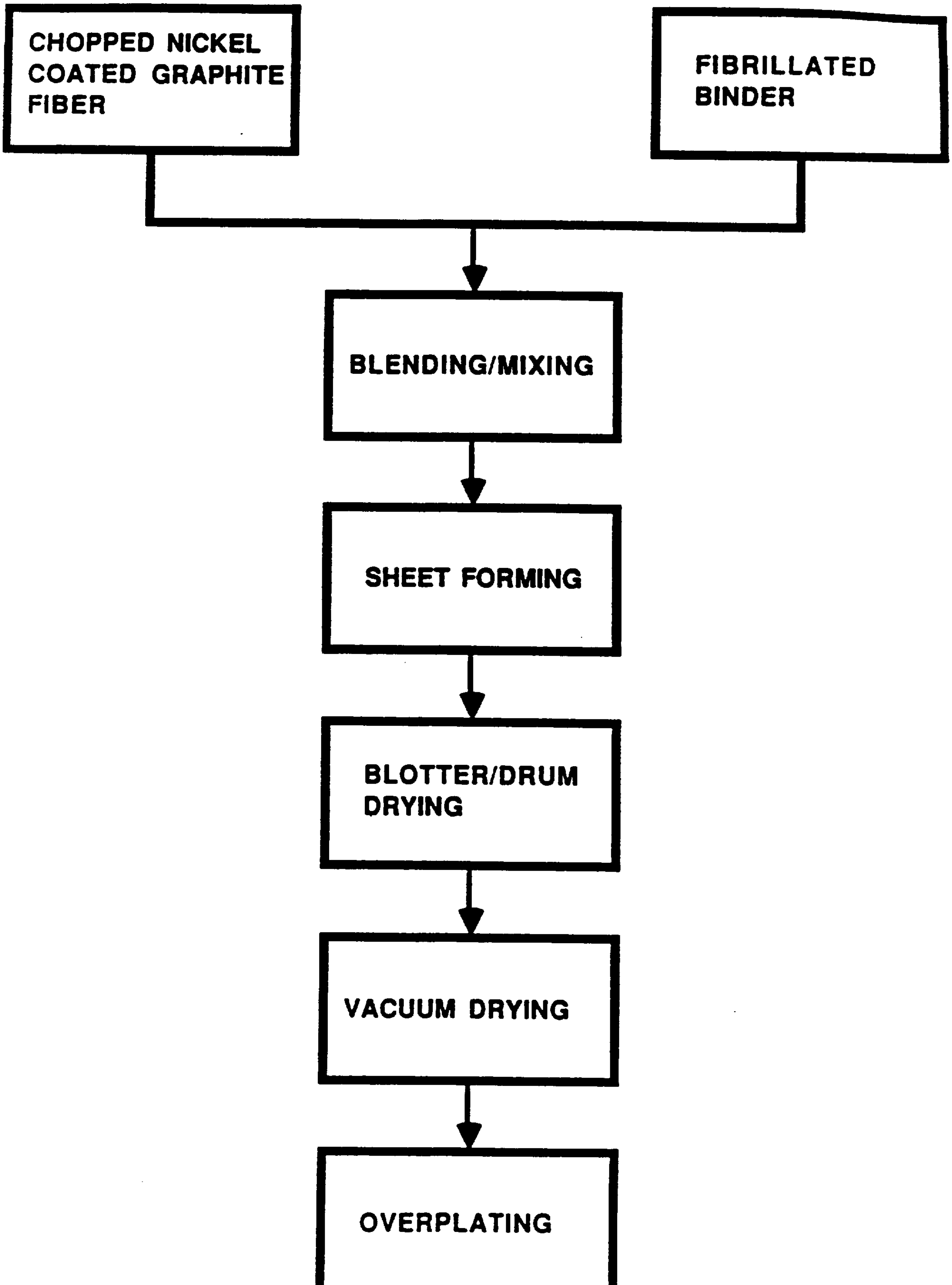


FIGURE 6. LIPKA

FIGURE 7. LIPKA

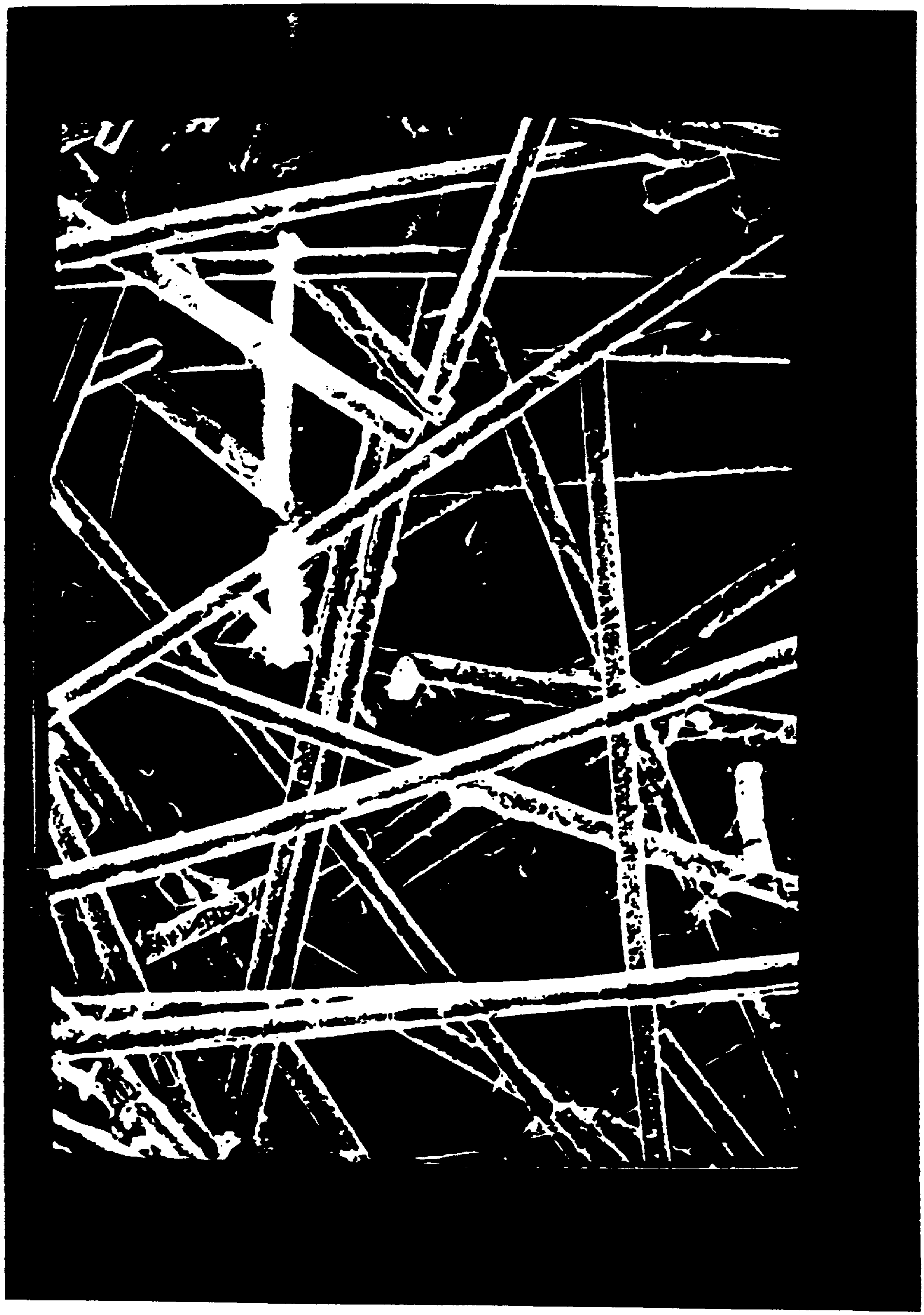
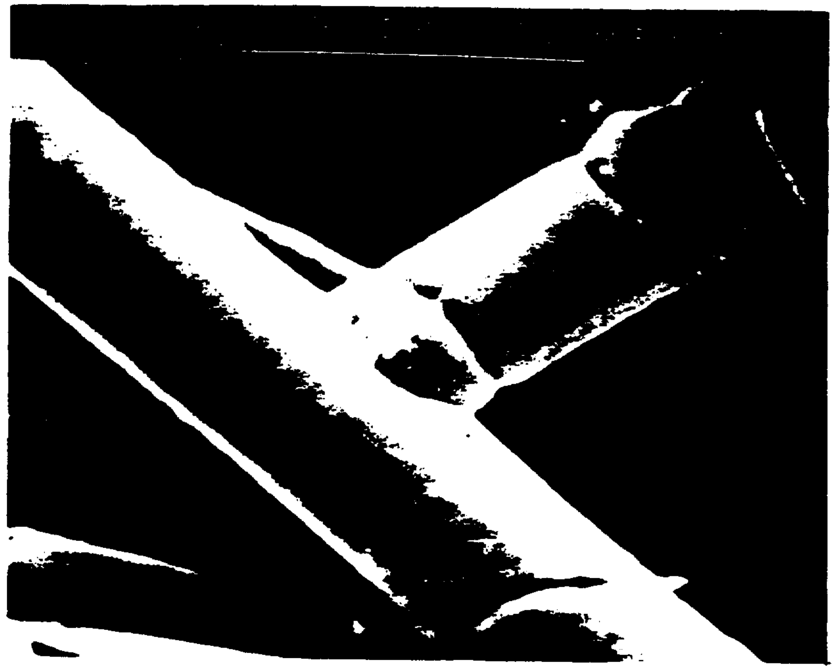
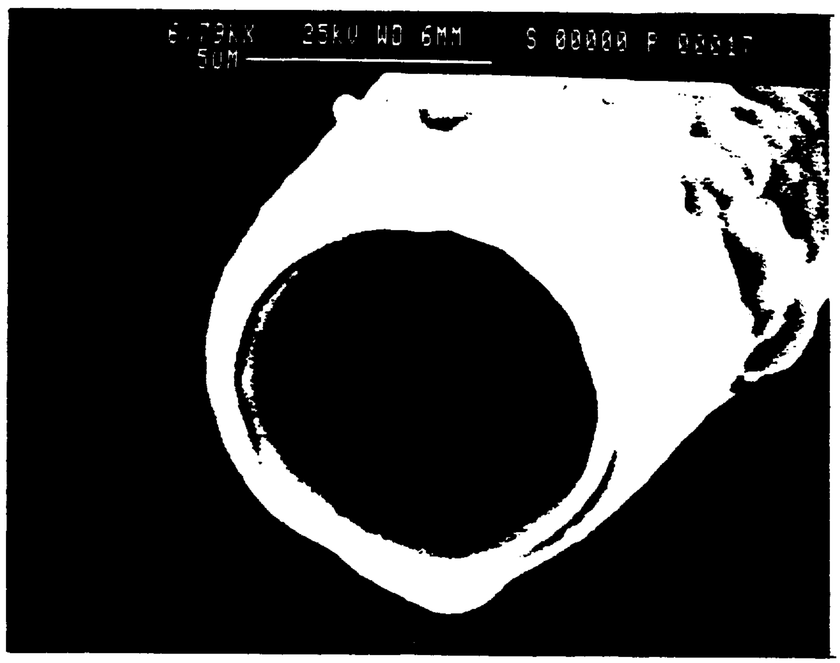


FIGURE 8. LIPKA

FIGURE 9. LIPKA



SURFACE **[2.42 KX]**



CROSS SECTION **[6.79 KX]**

OVERPLATED NCG MAT SHOWING EVIDENCE OF METALLURGICAL BONDING AND UNIFORMITY OF OVERPLATED NICKEL

FIGURE 10. LIPKA

PROPERTIES OF NICKEL COATED GRAPHITE FIBER STRUCTURES

	AS-CAST	OVERPLATED
WEIGHT (g/m^2)	126	226-550 (720-2,900 A-s)
BULK DENSITY (g/cm^3)	0.16	0.20-0.50 (180-2,200 A-s)
ELECTRICAL RESISTIVITY ($m\Omega$ - cm)	63	3.2-0.62 (48-420 g/m^2) (0.6-2.1 μm)
PERCENT POROSITY	94	92
MEDIAN PORE DIAMETER (μm)	44	45

FIGURE 11. LIPKA

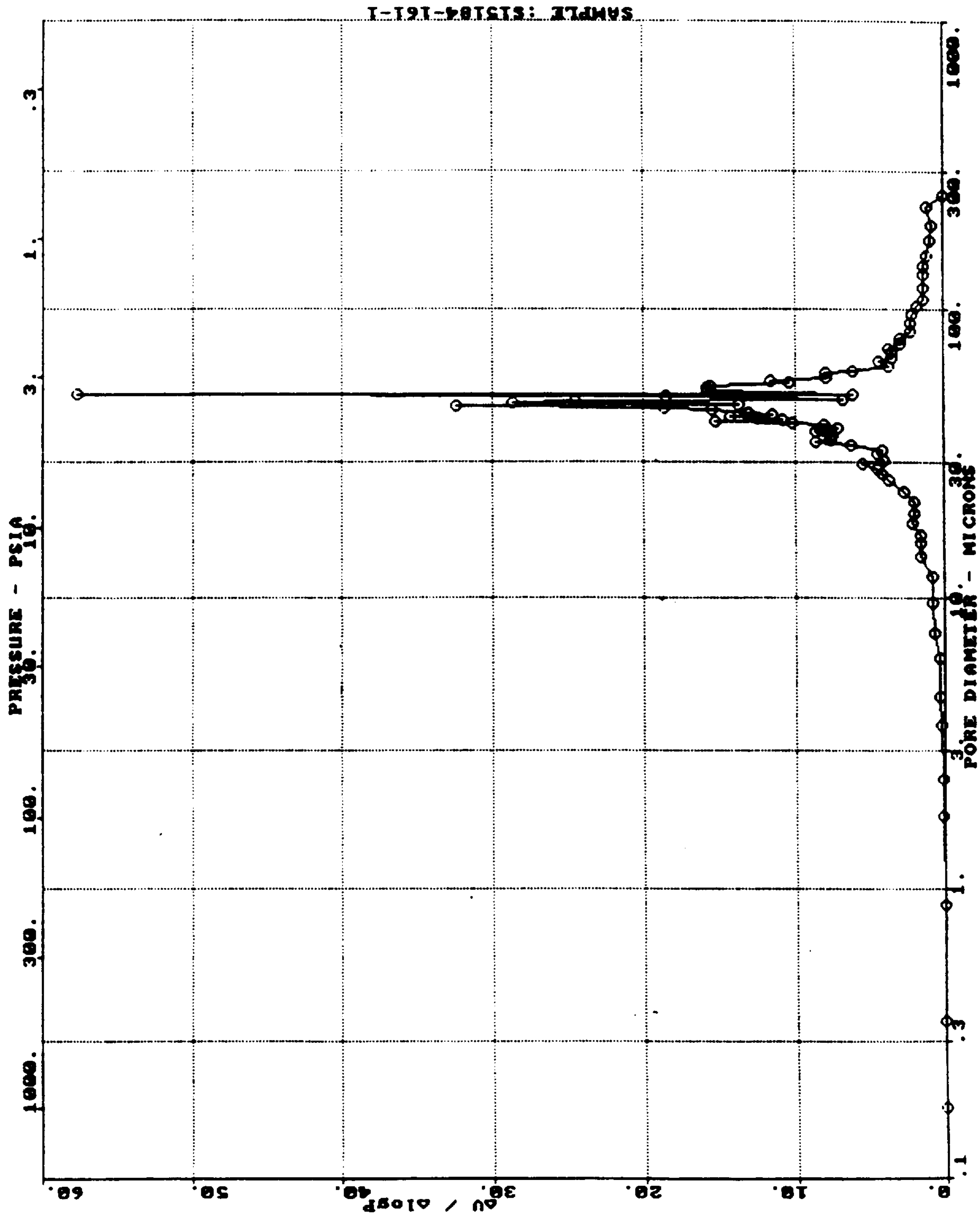


FIGURE 12. LIPKA

NCG ELECTRODE PERFORMANCE RESULTS TO DATE

- **Volumetric Energy Density**

  Up to 415 mAh/cc at C/10 Rate

- **Gravimetric Energy Density**

  Up to 243 mAh/g at C/10 Rate

- **Active Mass Utilization**

  Up to 95% of Theoretical Discharge Capacity at C/10 Rate

- **Cycling Characteristics**

  Approximately 600 Cycles to Date Without Performance Degradation

FIGURE 13. LIPKA

SUMMARY

- PAPERMAKING TECHNOLOGY CAN BE USED TO PREPARE HIGH POROSITY STRUCTURES USING NICKEL COATED GRAPHITE FIBERS
- POROSITY AND MEDIAN PORE DIAMETER DETERMINED BY PAPERMAKING PROCESS
- OVERPLATING PROCESS PREDICTABLE AND CONTROLLABLE
- OVERPLATING/FIBRILLATED BINDER 'HOLD' MAT TOGETHER
- OVERPLATING INCREASES ELECTRICAL CONDUCTIVITY OF MAT THROUGH METALLURICAL BONDING
- NICKEL COATED GRAPHITE FIBER ELECTRODES DISPLAY EXCELLENT SPECIFIC CAPACITY

FIGURE 14. LIPKA

ACKNOWLEDGEMENT

- T. TRAN FOR PERFORMING THE EXPERIMENTAL WORK

- POROUS MATERIALS, INC. FOR THE MERCURY PYCNOMETRY AND POROSIMETRY ANALYSIS

FIGURE 15. LIPKA

"ISSUES REGARDING IN-ORBIT RECONDITIONING"

KARLA CLARK

Karla Clark (JPL) gave the presentation "Issues Regarding In-Orbit Reconditioning," in particular whether it is advisable for LEO type missions. Reconditioning has been accepted for GEO applications but is still debated for LEO applications. There are different types of reconditioning. It may involve partial discharge (capacity check) done on a pack basis or individual cell basis. Or it may involve deep discharge.

There are advantages and disadvantages in reconditioning. The advantages include increases in the EODV, Wh efficiency (lower effective DOD), and coulombic efficiency. There is also a temporary "fix" of low voltage problem. There are disadvantages associated with reconditioning. There are increases in the cost, complexity, operational costs, and weight. For LEO orbit or where there is no 100% sun time for an adequate period, either the loads must be decreased or DOD must be increased in other batteries for one battery to be reconditioned.

There are unknowns in reconditioning. One does not know what is the best hardware for reconditioning or the most effective reconditioning schedule. The long term effects of reconditioning on cycle life is still debatable.

Before one considers reconditioning, one must examine the effect of low battery voltage on both regulated and unregulated bus. One must weigh the effect of reconditioning against non-recurring costs, recurring costs, operational costs, and weight.

Because each mission is unique, whether to recondition or not depends on budget, power system design, spacecraft design, mission design, and operational constraints. Clark concluded by saying that reconditioning is not advisable for every LEO type of missions.

Comment: Gaston (RCA) A spacecraft with just one battery cannot have reconditioning because it is needed all the time. If there is more than one battery, reconditioning is helpful provided that there is a long mission. Reconditioning on a 26.5 amp-hour cell was presented some years ago. The cell showed increased voltage. Reconditioning seems to be beneficial. It can be done in LEO just as in GEO. It's not a new development nor is it expensive. Many spacecraft have onboard computers that can signal when to do reconditioning so that a ground crew will not be needed to perform monitoring.

Comment: Methlie (U.S. Govt): The higher the discharge rate and the higher the cutoff level is set, the more often reconditioning is needed. The higher the charge rate, the less often reconditioning is needed. There could be from 30 to 90 days for reconditioning.

Clark asked interested manufacturers to get in touch with her.

JPL

ISSUES REGARDING IN-ORBIT RECONDITIONING

1987 NASA/GSFC BATTERY WORKSHOP

PRESENTED BY

KARLA B. CLARK

JET PROPULSION LABORATORY

NOVEMBER 4, 1987

FIGURE 1. K.CLARK

JPL

IS RECONDITIONING ADVISABLE FOR LEO TYPE MISSIONS ?

FIGURE 2. K.CLARK

JPL

BACKGROUND

AREA OF DISCUSSION: LEO TYPE MISSIONS

RECONDITIONING TYPES:

- PARTIAL PACK - CAPACITY CHECK
- PARTIAL CELL - CAPACITY CHECK
- DEEP PACK - PACK TO LOW VOLTAGE
- DEEP CELL - CELL TO LOW VOLTAGE

RECONDITIONING ACCEPTED FOR GEO APPLICATIONS

RECONDITIONING DEBATED FOR LEO APPLICATIONS

FIGURE 3. K.CLARK

JPL

WHAT ARE THE REAL QUESTIONS ?

Q: HOW DOES RECONDITIONING FUNDAMENTALLY AFFECT CELL?

A: HOTLY DEBATED ISSUE.

Q: GIVEN ANSWER TO ABOVE, SHOULD WE IMPLEMENT RECONDITIONING IN LEO TYPE FLIGHT PROJECTS ?

FIGURE 4. K.CLARK

JPL

ADVANTAGES OF RECONDITIONING

- INCREASED EODV
- INCREASED WHr EFFICIENCY
  - LOWER EFFECTIVE DOD
- TEMPORARILY ALLEVIATE LOW VOLTAGE PROBLEMS
- APPARENT INCREASE IN COULOMBIC EFFICIENCY

FIGURE 5. K.CLARK

JPL

DISADVANTAGES OF RECONDITIONING

- INCREASED COST OF SYSTEM
- INCREASED COMPLEXITY OF SYSTEM
- INCREASED OPERATIONAL COST
- INCREASED WEIGHT
- POTENTIAL DECREASE IN SYSTEM RELIABILITY (HARDWARE COUNT)
- IF NO 100 % SUN TIME AVAILABLE:
  - INCREASE DOD OF OTHER BATTERIES
  - DECREASE LOADS
- IMPROVEMENT IN VOLTAGE PERFORMANCE IS TEMPORARY (?)

FIGURE 6. K.CLARK

JPL

UNKNOWNS

- BEST HARDWARE IMPLEMENTATION
- MOST EFFECTIVE SCHEDULE OF RECONDITIONING
- LONG TERM EFFECTS OF RECONDITIONING ON CYCLE LIFE
- RELATIONSHIP OF OPERATING CONDITIONS AND RECONDITIONING NEEDS
- RELATIONSHIP OF HARDWARE DESIGN/CONSTRAINTS AND RECONDITIONING NEEDS
- EFFECT ON CELL CAPACITY AT HIGH RATE TO 1.0 V
- EODV BEHAVIOR IN DEGRADATION VERSUS IN-COMPLETE RECHARGE

FIGURE 7. K.CLARK

JPL

CONSIDERATIONS

- EFFECT OF BATTERY LOW VOLTAGE ON:
  - REGULATED BUS
  - UNREGULATED BUS

- EFFECT OF RECONDITIONING SCENARIO ON:
  - NON-RECURRING COSTS
  - RECURRING COSTS
  - OPERATIONAL COSTS
  - WEIGHT

FIGURE 8. K.CLARK

JPL

SUMMARY

- EACH MISSION DECISION IS UNIQUE

- DECISION DEPENDS ON:
  - BUDGET
  - POWER SYSTEM DESIGN
  - SPACECRAFT DESIGN
  - MISSION DESIGN
  - OPERATIONAL CONSTRAINTS

- RECONDITIONING IS NOT ADVISABLE FOR EVERY LEO TYPE MISSION

FIGURE 9. K.CLARK

THURSDAY, NOVEMBER 5, 1987
(MORNING SESSION)

"UPDATED LIFE TEST RESULTS FOR THE AUSSAT NiCd BATTERY CELLS USING PELLON 2505 AND FS2117 SEPARATORS"

DAVE BAER

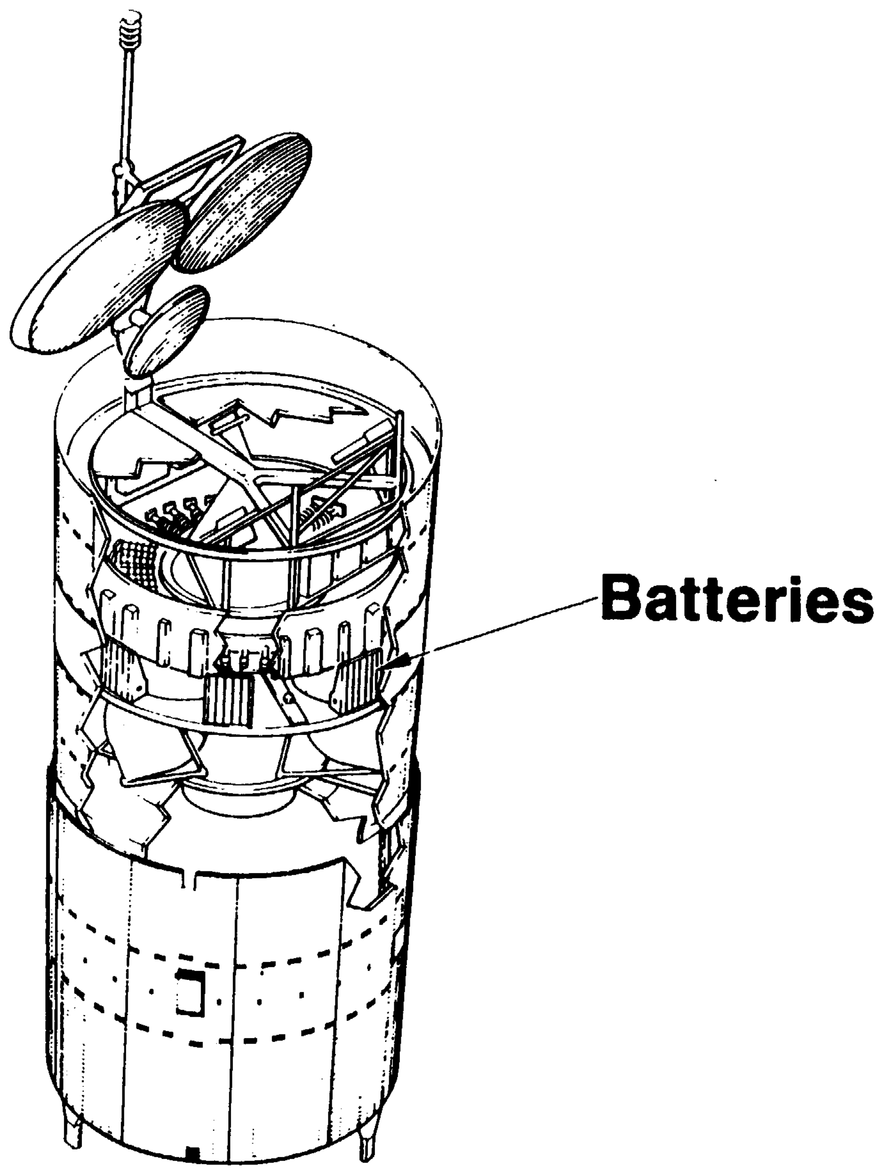
Dave Baer continued to chair the continuation of the NiCd program. He also gave the presentation on the "Updated Life Test results for the Aussat NiCd Battery Cells using Pellon 2505 and FS2117 separators."

Aussat had two batteries, each battery consisted of four packs of eight cells each with mylar wrap (2 pieces) insulating each cell (Baer [Figure 2]). They used the 2505 separator. The NiCd battery cell had only one ceramic seal (on the positive terminal) (Baer [Figure 3])

Baer [Figure 4] shows the comparison between typical separator properties for the 2505 and the FS2117. The qualification sequence, (Baer [Figure 6]), consists of pre-environmental testing of cell properties, environmental testing, and post-environmental testing, again of cell properties. There appeared to be no difference between the 2505 and the FS2117 separators.

The real-time eclipse test, (Baer [Figure 7]), was conducted for 20 GEO eclipse seasons. The real-time charging schemes, (Baer [Figure 9]), involved ten seasons of charging at high and medium rates with 115 to 120 percent charge return at 5 degrees C. Reconditioning charge capacities were generally good. EOD and peak voltages of the two types of separators tracked well in the real-time test. In the throughput test, (Baer [Figures 12, 13, and 14]), EOD and peak charge voltages, one cell's voltage dropped below 1.0 V at cycle 600. A reconditioning cycle was done, (Baer [Figure 10]), and then the cell worked well thereafter.

Later, post testing was done. The voltage recovery was fine. Although some charge voltages were a bit high during C/10 charge at 5 degrees C and C/20 at 0 degrees C. There was no evidence of Hydrogen gassing. In the post testing analysis one cell of each type was analyzed, and the results were very similar. In conclusion, there is very little difference between the two separators.



HUGHES

Aussat Spacecraft

On-orbit configuration

856806-2

AUSSAT

FIGURE 1. BAER

Battery Pack Construction

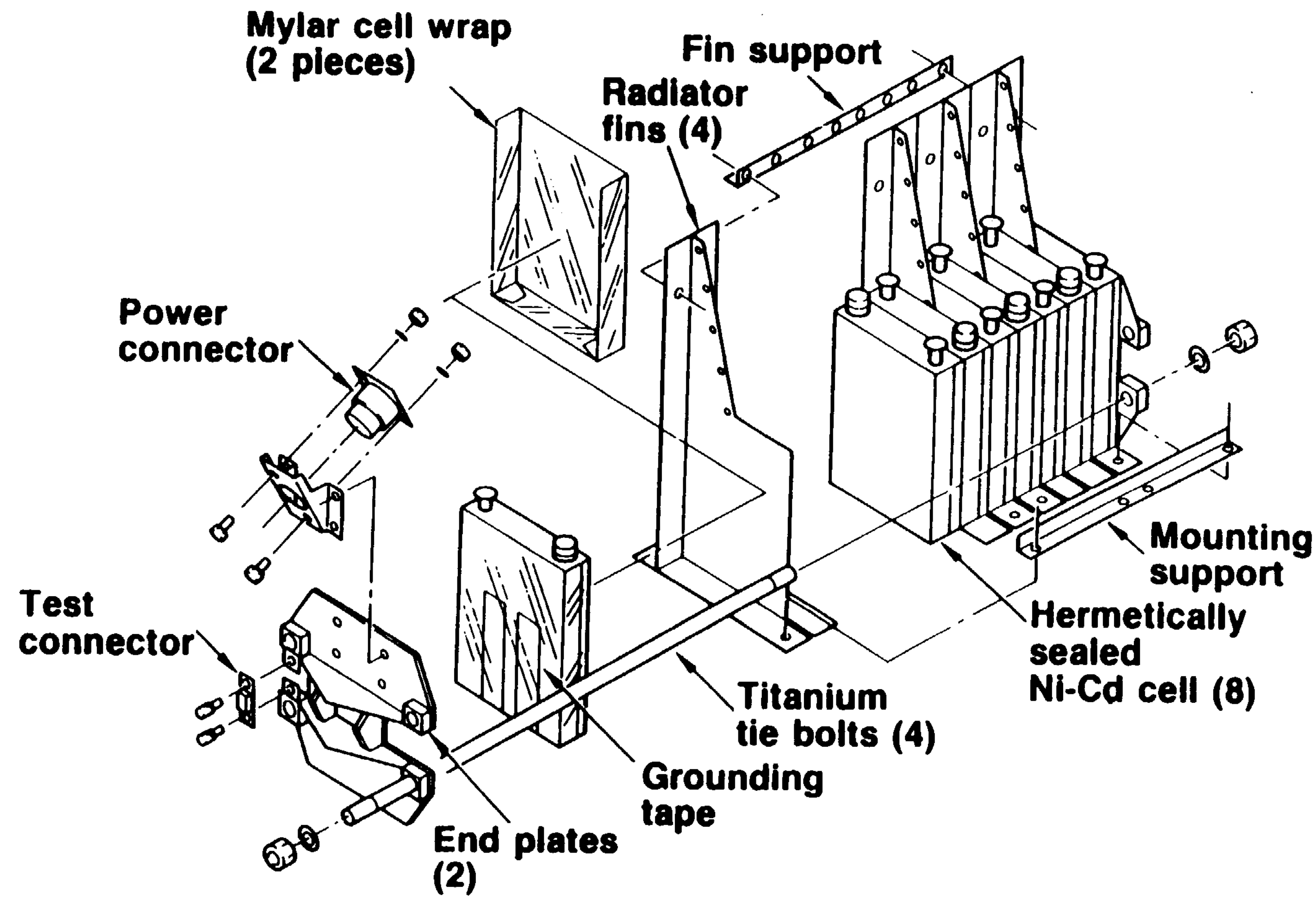
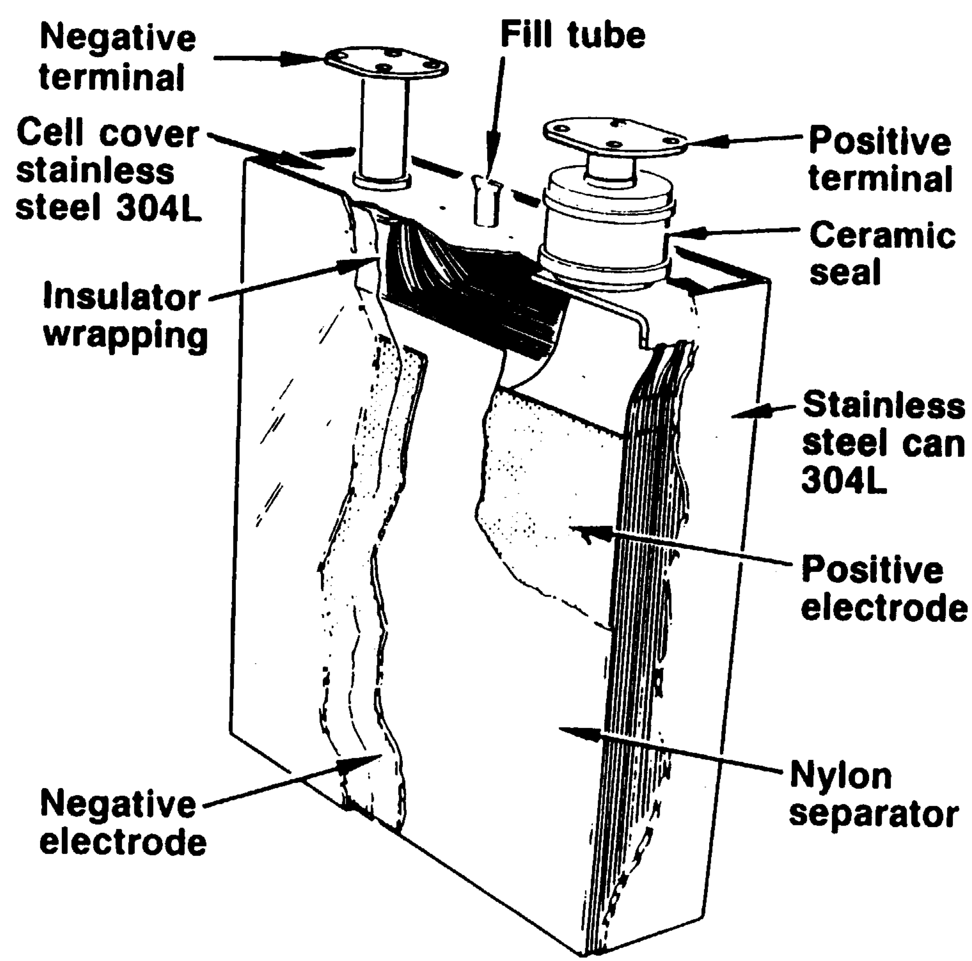


FIGURE 2. BAER

Nickel Cadmium Battery Cell



856806-4

FIGURE 3. BAER

AUSSAT

Separator Properties (Typical)

HUGHES

	2505	FS2117
Filament	Nylon 6	⅓ Nylon 6 ⅔ Nylon 66
Weight, g/m^2	60 ± 8	74
Thickness, mm	0.38 ± 0.07	0.30
Electrolyte absorbed, wt %	800 (min)	580
Air permeability	200 (min)	142
Bonding method	Chemical	Heat
Calendaring	No	Yes

856806-5

FIGURE 4. BAER

AUSSAT

Aussat Battery Qualification Program

HUGHES

1 battery = 4 packs of 8 cells each

- 2 packs = FS2117 separator
- 2 packs = 2505 separator

856806-6

FIGURE 5. BAER

AUSSAT

Qualification Test Sequence

HUGHES

Pre-environmental testing

- Cell properties

Environmental testing

- Sine vibration
- Random vibration
- Thermal vacuum (0^0 C to 26^0 C)
- Charge/discharge performance test at hot and cold

Postenvironmental testing

- Cell properties

856806-7

FIGURE 6. BAER

AUSSAT

Real-time Eclipse Test

HUGHES

- 20 geosynchronous eclipse seasons

  Real time eclipse

  - 46 days, max eclipse 70 min
  - Discharge - 12 A
  - Charge - 2 A to 100% charge return

  Shortened solstice

  - 14 days

  Recondition before each season

856806-9

FIGURE 7. BAER

HUGHES

Pack no.	Cell no.	Lot no.	Separator	Test	Comments
1	1-8	2	2505	Qualification Real Time	
2	1-8	2	FS2117	Qualification Real Time	
3	1-8	2	2505	Qualification Real Time	
4	1-8	2	FS2117	Qualification	
5	1	2	FS2117	Real Time	Removed for analysis after 7 cycles
	2	2	FS2117	Real Time	
	3	3	2505	Real Time	
	4	3	2505	Real Time	
	5	4	2505	Real Time	
	6	4	2505	Real Time	
	7	5	2505	Real Time	
	8	5	2505	Real Time	

FIGURE 8. BAER

HUGHES

Season	Rate (AMPS)		Charge Return
1	High	(2.0)	115%
2	High	(2.0)	115%
3	High	(2.0)	11[illegible]%
4	High	(2.0)	107%
5	Medium	(1.2)	115%
6	High	(2.0)	11[illegible]%
7	High	(2.0)	11[illegible]%
8	High	(2.0)	11[illegible]%
9	Medium	(1.2)	120%
10	Medium	(1.2)	120%

FIGURE 9. BAER

HUGHES

Season	Pack 1 (2505)	Pack 2 (2117)	Pack 3 (2505)	Pack 4 (2505/2117)	Discharge Scheme
1	35.31	35.64	34.94	36.23	17.4Ω to 1.15V 15.2Ω to 1.00V
2	37.43	37.20	37.20	37.58	17.4Ω to 1.15V 15.2Ω to 1.00V
3	33.18	33.02	33.34	31.78	12.0A to 1.00V
4	32.60	32.60	33.40	31.80	12.0A to 1.00V
5	32.82	32.50	32.26	31.56	12.0A to 1.00V
6	36.25	36.40	35.37	33.64	17.4Ω to 1.15V 15.2Ω to 1.00V
7	34.42	36.00	36.12	33.78	25Ω to 1.00V
8	37.57	38.34	38.12	35.26	25Ω to 1.00V 50Ω to 1.00V
9	38.19	38.69	38.06	35.40	25Ω to 1.00V 50Ω to 1.00V

FIGURE 10. BAER

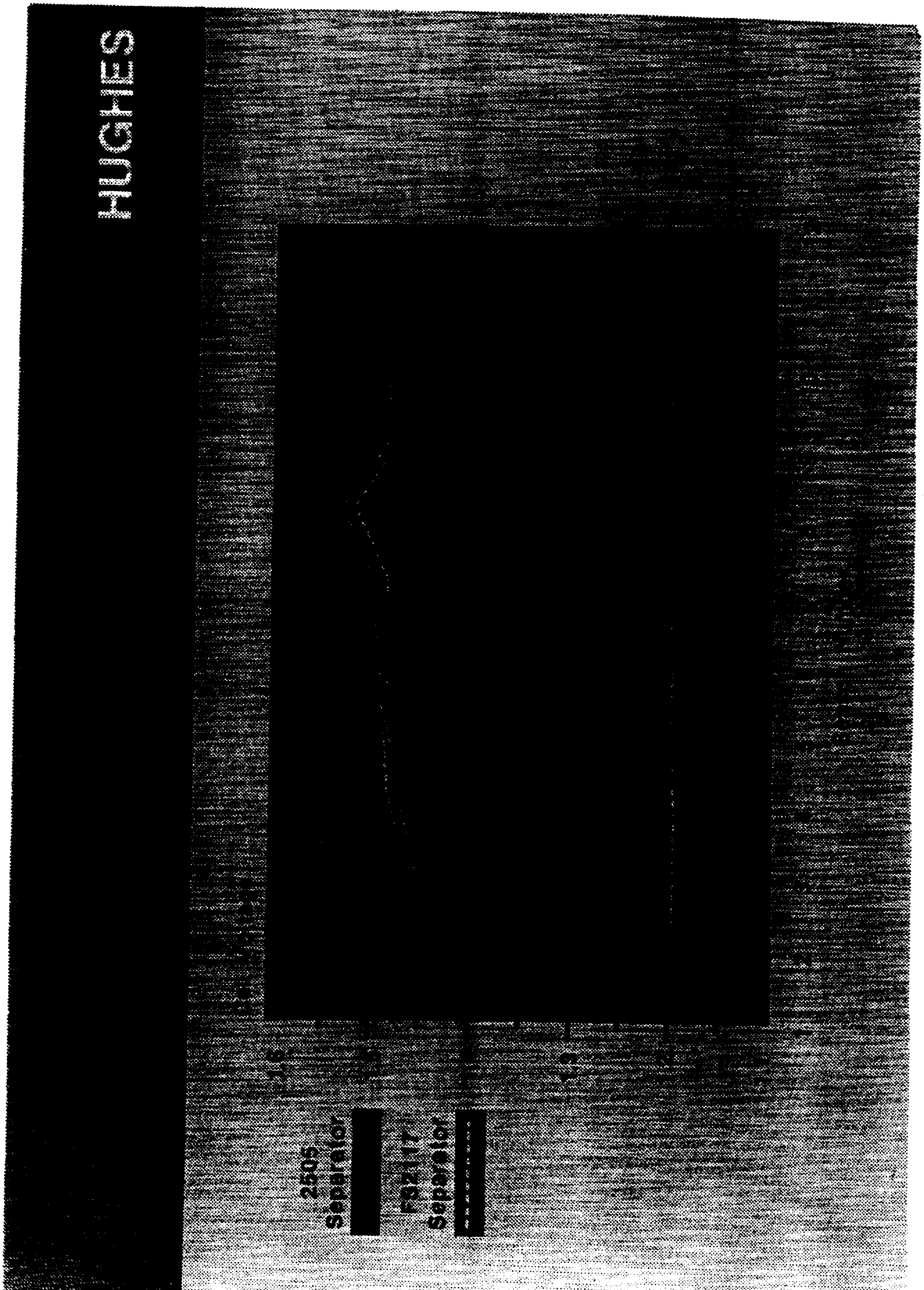


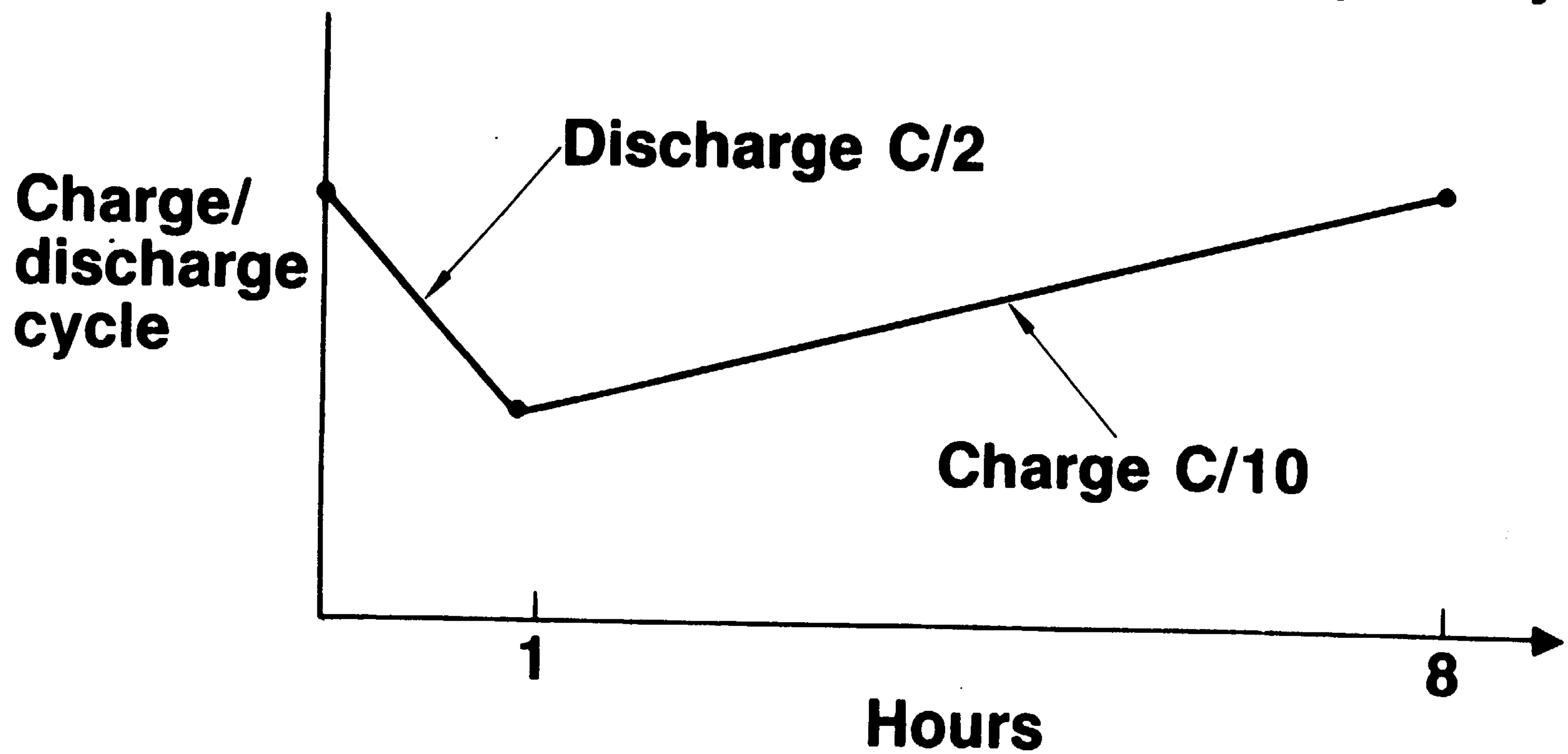
FIGURE 11. BAER

AUSSAT

Throughput Test

HUGHES

- 900 charge/discharge cycles, 3 cycles per day



856806-8

FIGURE 12. BAER

HUGHES

Cell no.	Lot no.	Separator	Pressure Gauge	Comments
1	1	FS2117	Yes	
2	1	FS2117	No	Teardown after 900 cycles
3	1	2505	Yes	
4	1	2505	No	
5	1	2505	No	Lowest EOD voltage Teardown after 900 cycles
6	1	2505	No	Teardown after 362 cycles
7	2	2505	Yes	
8	2	2505	No	
9	2	2505	No	
10	3	2505	Yes	Teardown after 362 cycles

FIGURE 13. BAER

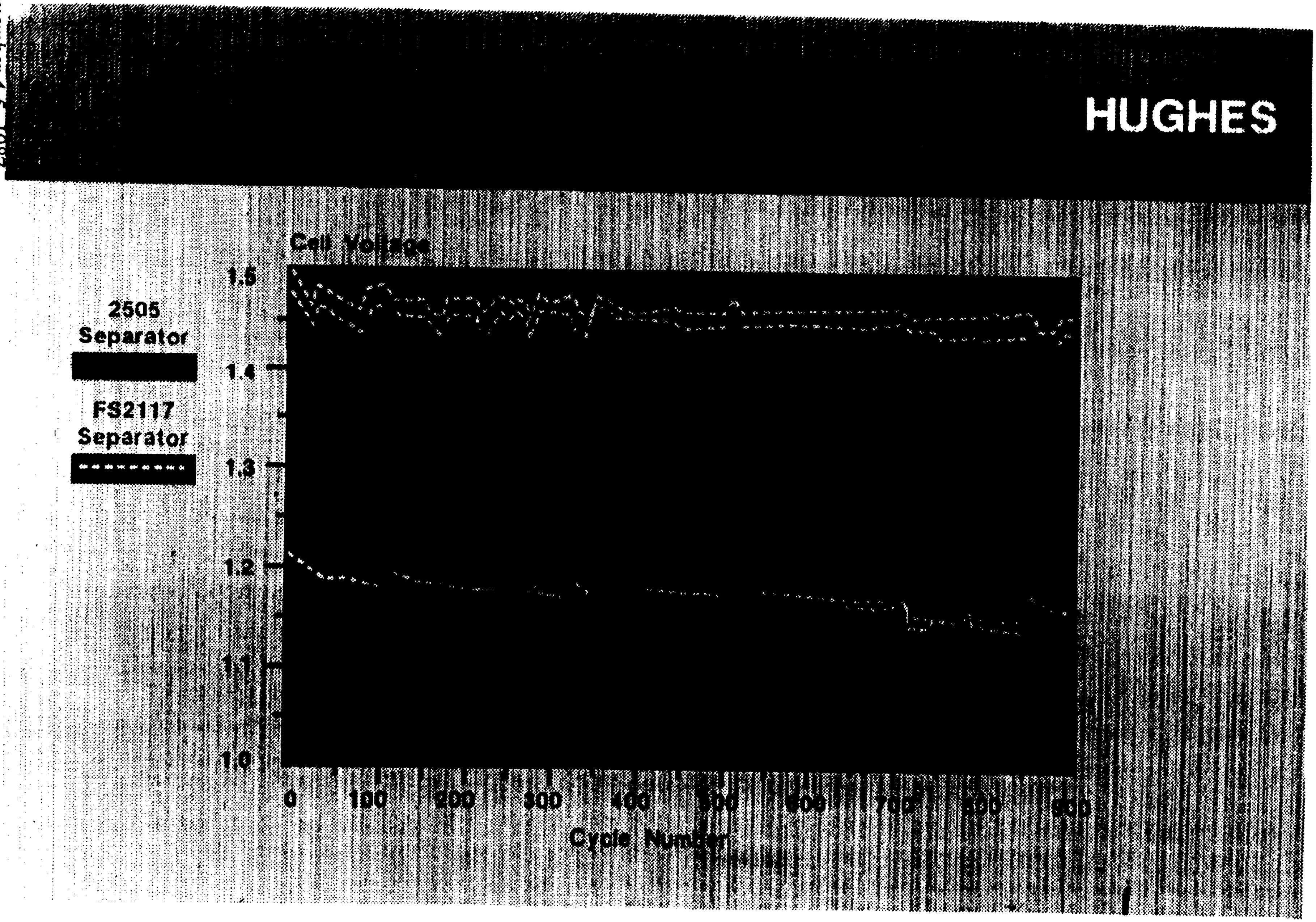


FIGURE 14. BAER

"LIFE TEST RESULTS OF A 12Ah NiCd FOR GEO APPLICATIONS"

CHARLES KOEHLER

Charles Koehler (Ford Aerospace) addressed the group on "Life Test Results of a 12Ah NiCd Battery for Geo Applications." The paper is drawn from a paper given at the IECEC. The 12 amp-hour NiCd cell was built by GE, Gainesville, FL (Koehler [Figure 2]). The life test was semi-accelerated (Koehler [Figure 3]). They used a 14-day accelerated solstice season. There was a bisequenced charge--5 minute charge and 5 minute discharge. The End-of-Discharge chart shows that the semi-accelerated test was done. Failure occurred in the 31st season. Fifteen years of life are shown. The cycling variation shown in the graph corresponds to seasonal changes. The sawtooth variation in one of the graphs is attributable to the test conditions. The cell stayed above 12 amp-hours (Koehler [Figure 10]). A DPA was done on some of the cells. There was some discoloration of the separators, but no sticking of the separators was found at EOL. Looking at the micrograph, no cracking appeared in the microstructure. Failure in the life test was caused by loss of overcharge protection. The test ran for five years and 31 seasons. (Koehler [Figure 13]).

Q. Thierfelder (GE): What kind of thermal chamber testing was done?

A. The battery was tested in an air-circulated thermal chamber. The air temperature was controlled to ~ 10 degrees C. The battery temperature was about 10 degrees C throughout the test.

Q. Maurer (Bell Labs.): How long was the cell at high discharge voltage--was there any bending or bulging of the cells?

A. Yes, the cells bulged quite severely, but did not break. There was no leaking or ruptured cells.

Q. Maurer (Bell Labs): Do you know what the voltages were when the bulging started?

A. No

LIFE TEST RESULTS OF A 12 AH Ni–Cd BATTERY FOR GEOSYNCHRONOUS ORBIT APPLICATIONS

C. KOEHLER & E. CRUZ

FIGURE 1. KOEHLER

Ford Aerospace &
Communications Corporation

12 Ah NICKEL-CADMIUM CELL DESIGN PARAMETERS

1.	RATED CAPACITY	12.0 Ah
2.	ELECTRODES	11 POSITIVE VACUUM IMPREGNATED 12 NEGATIVE TEFLONATED
3.	SEPARATORS	NON-WOVEN NYLON PELLON 2505
4.	ELECTROLYTE	31% BY WEIGHT KOH
5.	METAL CONTAINER	304L STAINLESS STEEL (0.012 INCH)
6.	COVER	304L STAINLESS STEEL (0.019 INCH)
7.	TERMINAL SEAL	DUAL METAL-CERAMIC (G.E. TYPE)
8.	ACTIVE MATERIAL LOADING POSITIVE PLATE NEGATIVE PLATE	 13.4 ± 0.6 g/dm2 16.06 ± 0.65 g/dm2
9.	PLATE THICKNESS POSITIVE NEGATIVE	 0.027 INCH 0.031 INCH
10.	FLOODED ELECTROCHEMICAL CAPACITY TOTAL POSITIVE TOTAL NEGATIVE	 14.4 - 16.8 Ah 22.8 - 30.0 Ah
11.	POSITIVE/NEGATIVE RATIO	1.6 MINIMUM

FIGURE 2. KOEHLER

Ford Aerospace & Communications Corporation

LIFE TESTING

Semi-Accelerated Test

- 42 charge/discharge cycles of 24 hours duration
- 0.51 to 1.20 hour eclipse duration per day
- 14 day storage mode between eclipse seasons

FIGURE 3. KOEHLER

Ford Aerospace & Communications Corporation

LIFE TESTING (Continued)

Electrical Conditions

- Eclipse discharge rate: 5.50A (C/2.18)
- Maximum depth of discharge: 55%
- Full charge rate: 0.86A to 120% return (bi-sequenced)
- Trickle charge rate: 0.29A (bi-sequenced)

FIGURE 4. KOEHLER

Ford Aerospace & Communications Corporation

LIFE TESTING (Continued)

Reconditioning

- Following odd numbered seasons
- Resistive discharge through 140 Ω load (C/48)
- Discharge until any cell reaches 0.75 $\pm$0.30 V

FIGURE 5. KOEHLER

Ford Aerospace & Communications Corporation

LIFE TESTING (Continued)

Biseasonal Capacity Determination

- Following even numbered seasons
- Forced discharge at 6.0A (C/2)
- Discharge until any cell reaches 0.75 ±0.30 V

FIGURE 6. KOEHLER

Ford Aerospace & Communications Corporation

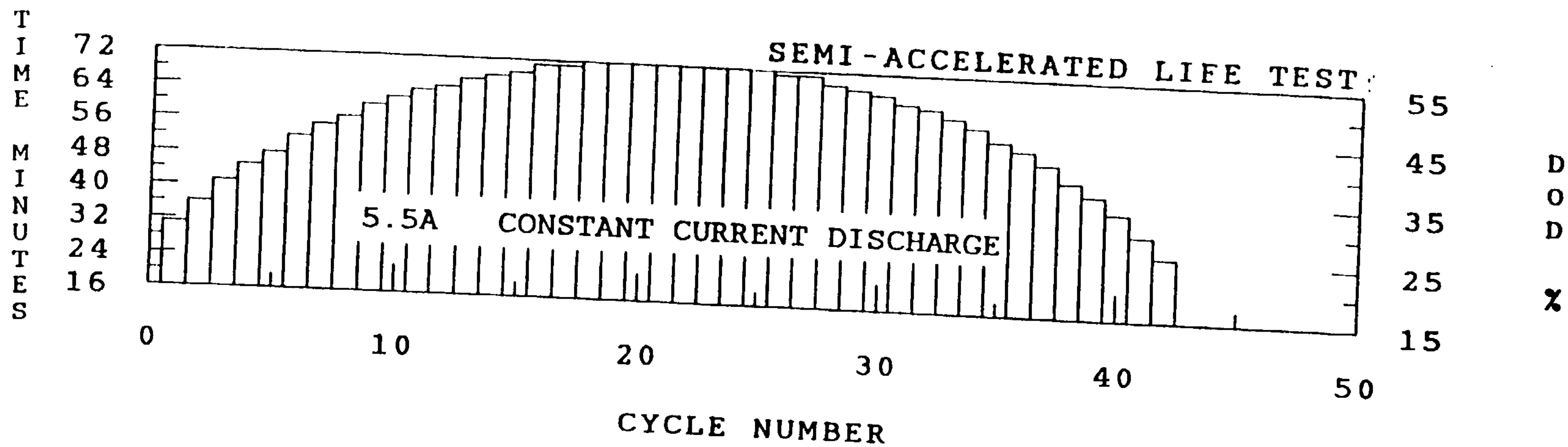


Figure 2a. Geosynchronous Orbit Eclipse Discharge Time and Battery Depth of Discharge.

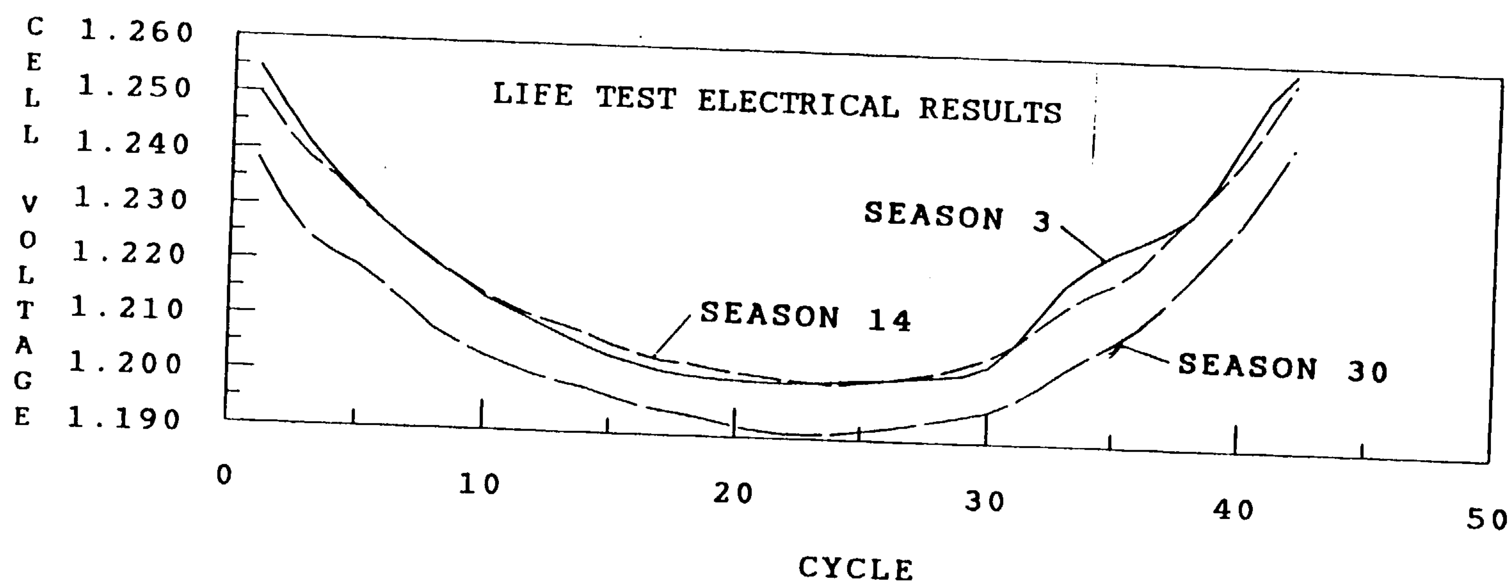


Figure 2b. End of Discharge Voltages for Three Seasons.

FIGURE 7. KOEHLER

Ford Aerospace & Communications Corporation

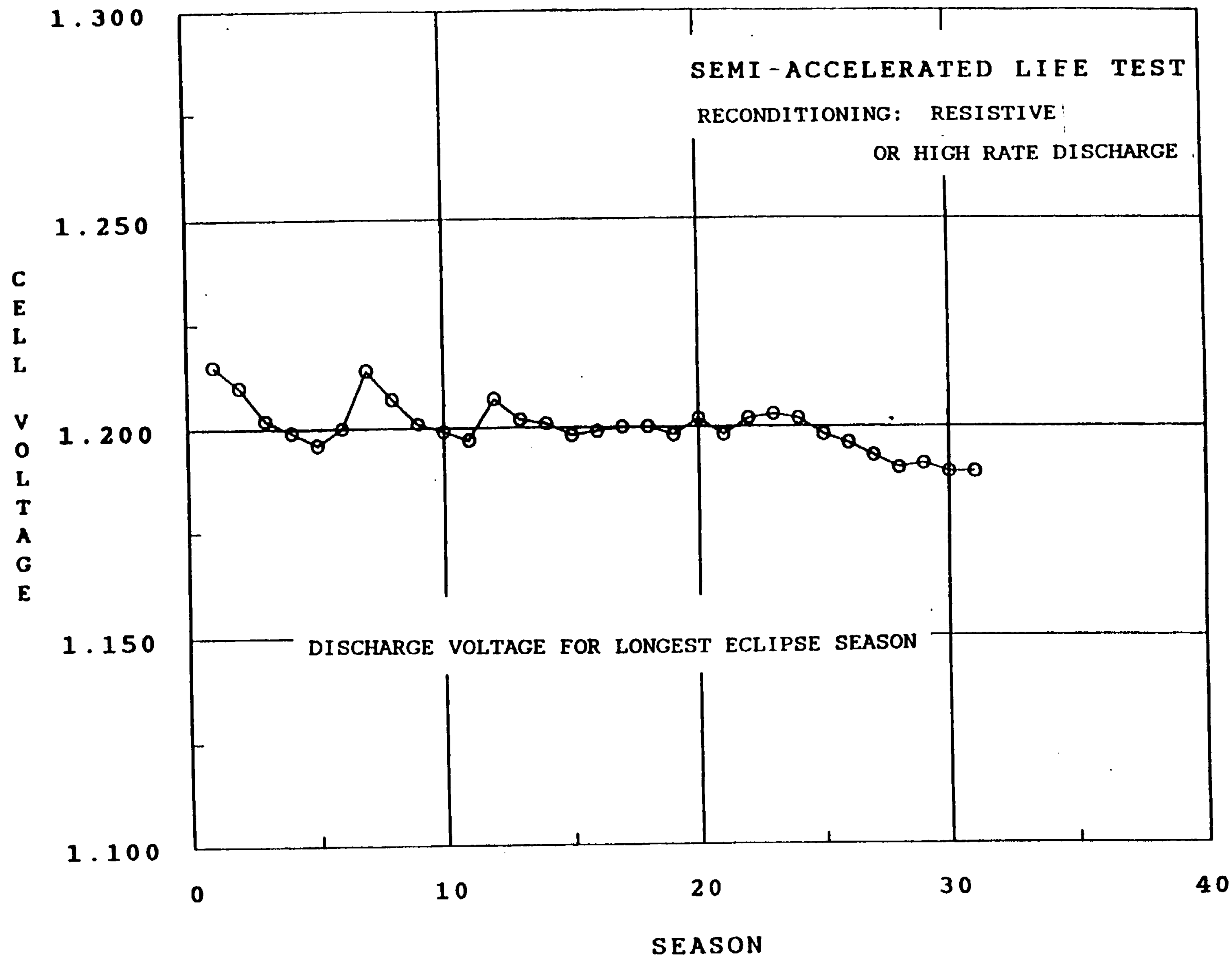


FIGURE 8. KOEHLER MINIMUM END OF DISCHARGE VOLTAGE TREND VS. EQUINOX SEASON.

Ford Aerospace & Communications Corporation

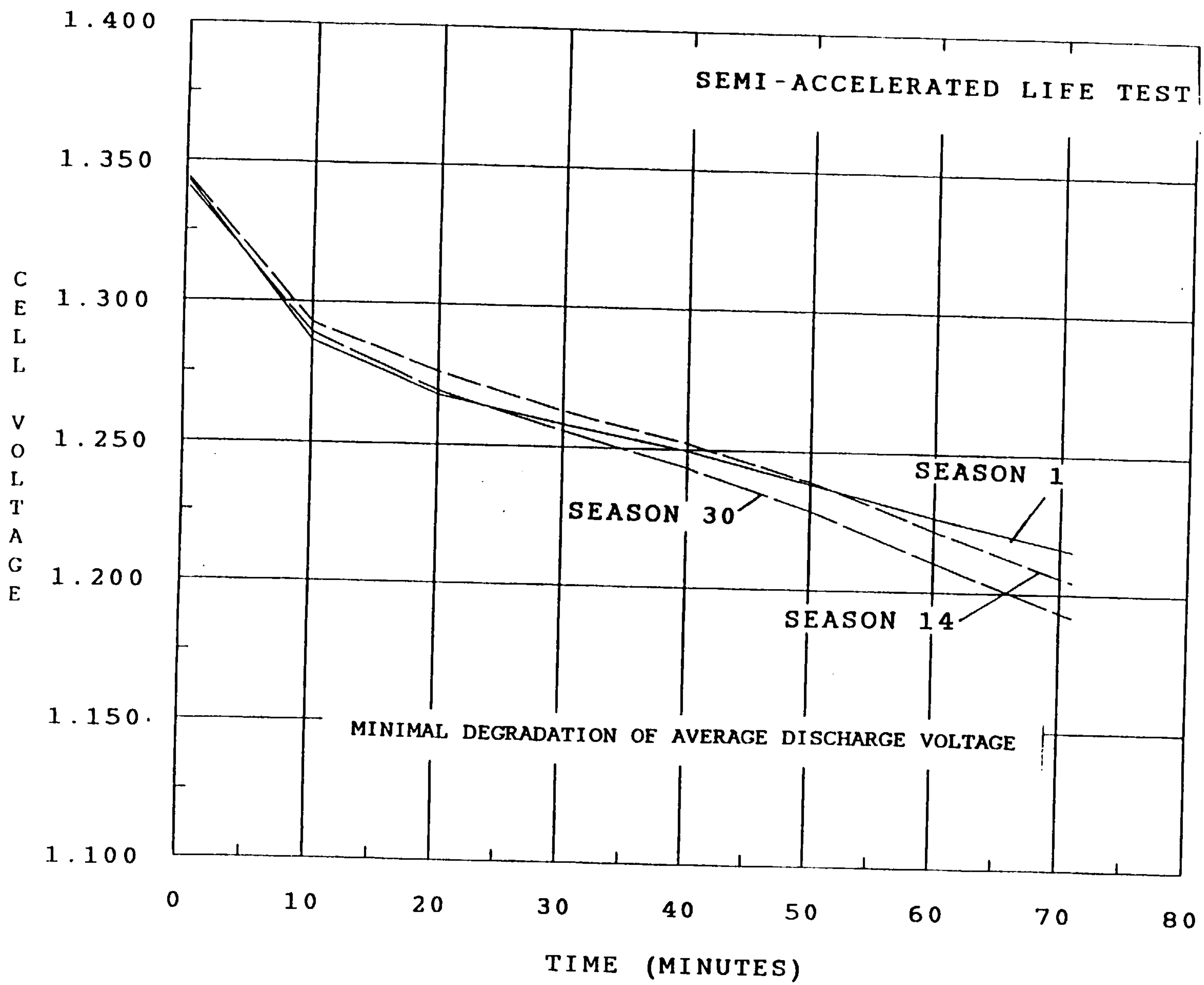


FIGURE 9. KOEHLER ECLIPSE DISCHARGE VOLTAGE PERFORMANCE VS. EQUINOX CYCLE.

Ford Aerospace & Communications Corporation

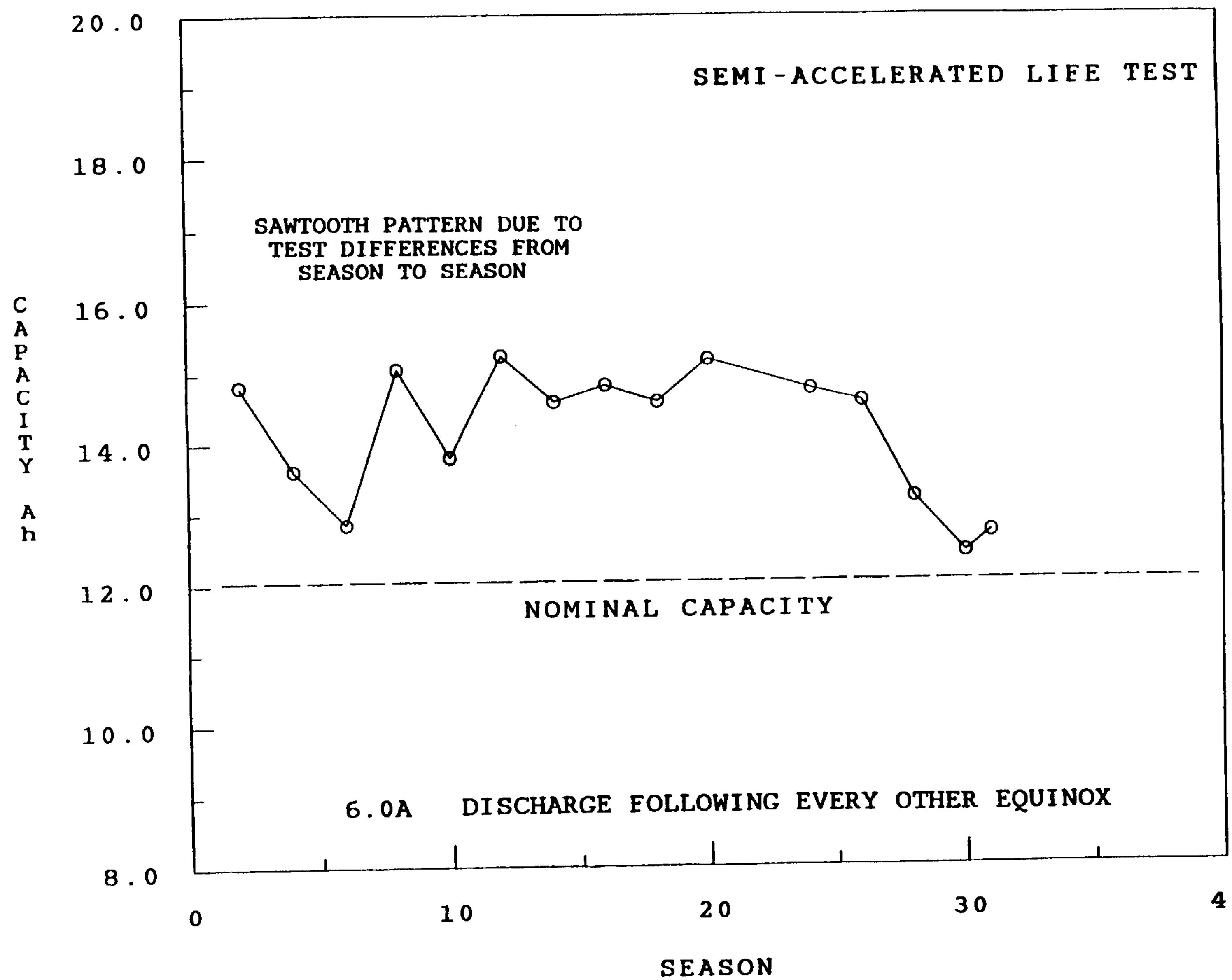
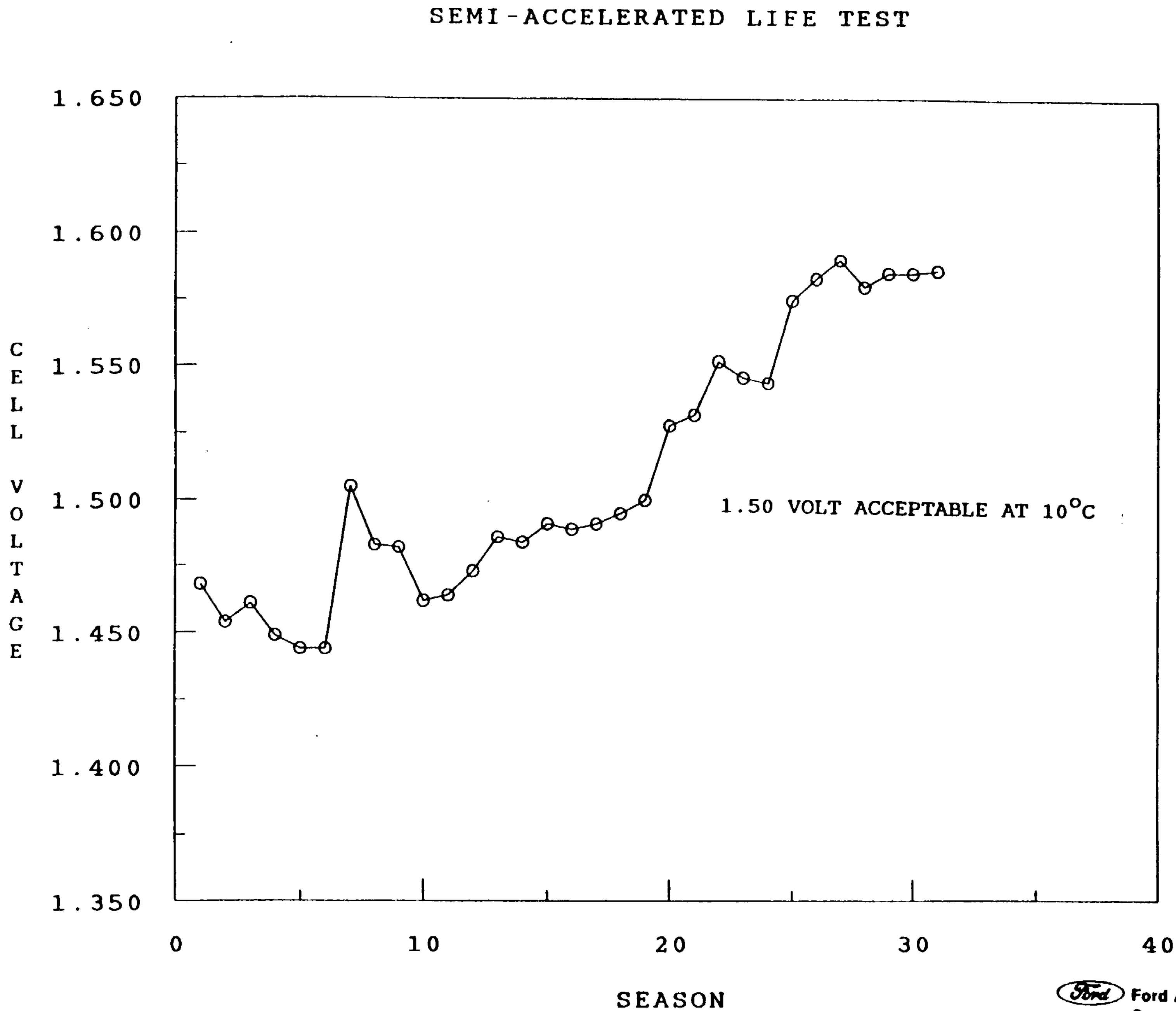


FIGURE 10. KOEHLER BATTERY CAPACITY VS. EQUINOX SEASON

Ford Aerospace & Communications Corporation



Ford Aerospace & Communications Corporation

FIGURE 11. KOEHLER PEAK CHARGE VOLTAGE TREND VS. EQUINOX SEASON.

Life Test of 12 Ah Ni-Cd
31 Semi-Accelerated Eclipse Seasons
15.5 yrs Equiv

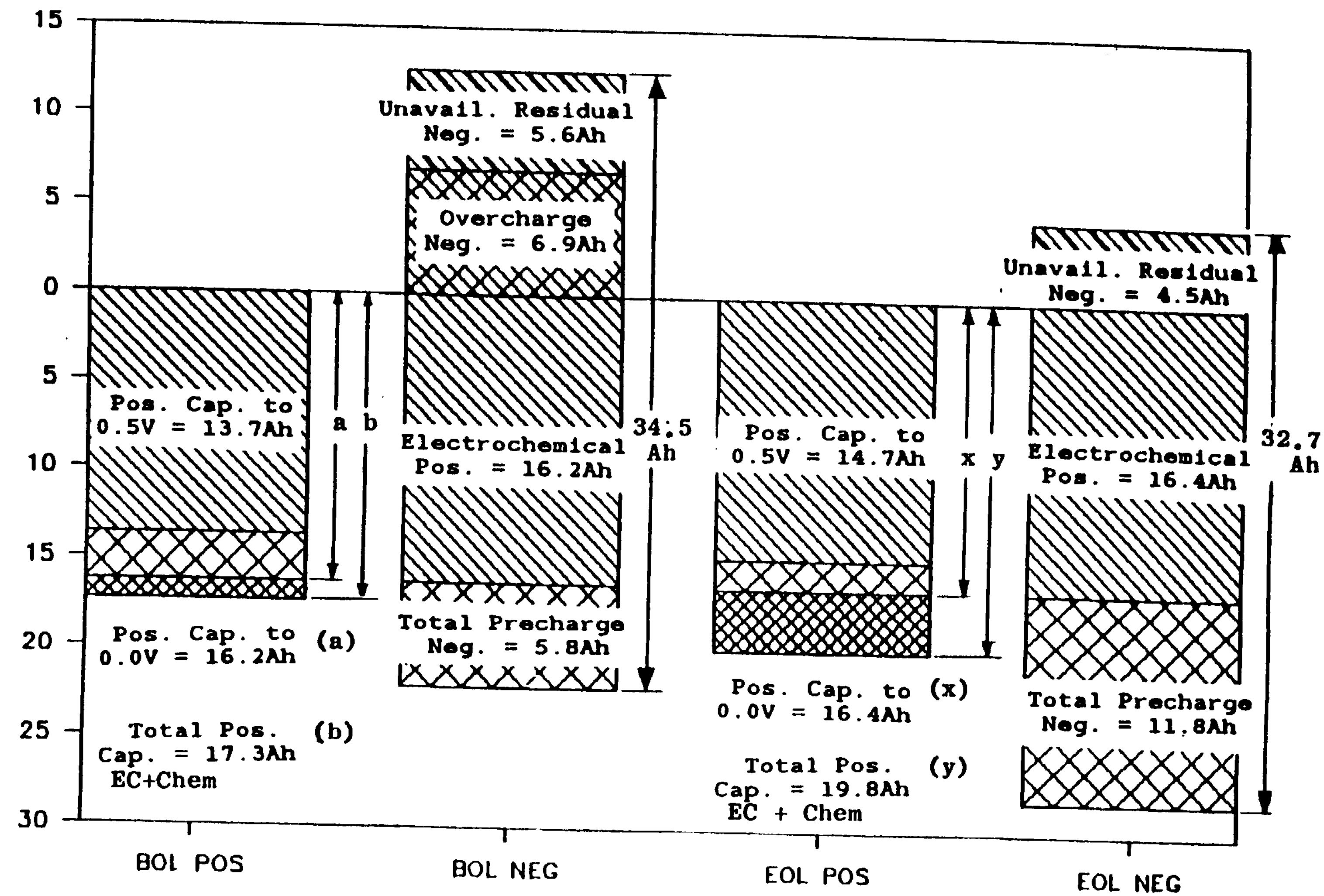


FIGURE 12. KOEHLER RELATIVE ELECTRODE ELECTROCHEMICAL BALANCE.

Ford Aerospace & Communications Corporation

CONCLUSIONS

- Battery underwent 31 semi-accelerated eclipse seasons
- Equivalent to 15 1/2 years of synchronous orbit operation
- Battery electrical performance
  - Good through seven years equivalent life
  - Acceptable through ten years equivalent life
- Battery failure mechanism: loss of overcharge protection

FIGURE 13. KOEHLER

LIFE TEST RESULTS OF A 12 AH NICKEL-CADMIUM BATTERY FOR GEOSYNCHRONOUS ORBIT APPLICATIONS

C. W. KOEHLER* & E. E. CRUZ
FORD AEROSPACE & COMMUNICATIONS CORPORATION
PALO ALTO, CALIFORNIA

ABSTRACT

The versatile nickel-cadmium battery design developed by Ford Aerospace & Communications Corporation for use on long life geosynchronous orbiting satellites has completed life testing. The 12 ampere-hour 28-cell assembly underwent 31 semi-accelerated eclipse seasons, representing 15.5 years of equivalent synchronous orbit eclipse cycling before failure. The cycling was performed at varying depths of discharge corresponding to the different discharge times with the maximum depth of discharge set at 55%. Test temperature was nominally 10°C.

This paper reviews the battery design, electrical performance during the life test, and compares pre-test and post-test chemical analysis of representative cells.

INTRODUCTION

Ford Aerospace & Communications Corporation has completed life testing of a universal 12 Ah nickel-cadmium battery assembly. The battery design is easily modified for specific spacecraft requirements and can accommodate unique voltage, thermal, and telemetry requirements and capabilities (Reference 1).

The life test, which is now complete, simulated a geosynchronous orbit for 31 semi-accelerated eclipse seasons. Each eclipse season consisted of 42 days of real time equinox simulation with varying depths of discharge up to 55% followed by an accelerated solstice season lasting 14 days. During the 14 day solstice reconditioning or capacity measurements were performed providing a state of health check on the battery.

The test was very successful confirming the battery design life requirement of 7 years in orbit at 55% depth of discharge.

BATTERY DESCRIPTION

The battery which underwent life testing is a 28-cell nickel-cadmium battery assembly having a nameplate capacity of 12 Ah. A detailed description of the battery assembly and reference performance data was provided in reference 1 and 2. Figure 1 shows a photograph of the battery assembly.

To summarize, the battery consists of 28 electrically connected cells in series with bypass diodes across each cell in the charge and discharge direction. The cells were manufactured by the General Electric Company, Battery Business Department, Gainesville, FL in 1979. The nickel electrodes are vacuum deposited with an active material loading of 13.4 +/- 0.6 g/dm2 while the cadmium electrodes have an active material loading of 16.06+/- 0.65 g/dm2 and are teflon treated. Non-woven nylon, Pellon 2505, is the separator material The electrolyte is 31% by weight potassium hydroxide without additives.

The cells design uses a low profile terminal seal. To reduce weight the cell container is 0.012 inch stainless steel. General characteristics of the cell are high negative/positive plate electrochemical capacity ratio, low soluble carbonates, minimum precharge level, high electrolyte quantity, and maximum overcharge protection consistent with cell capacity requirements.

The battery assembly utilizes the Ford Aerospace proven concept of cell support ribs, end plates, and tie rods for mechanical and thermal design. The cell support ribs provide a lightweight means for thermal dissipation by conduction to a baseplate radiator system and mechanical strength for mounting the battery to the spacecraft equipment panel. The end plate/tie rod structure provide compression the cells need to maintain interelectrode spacing throughout life.

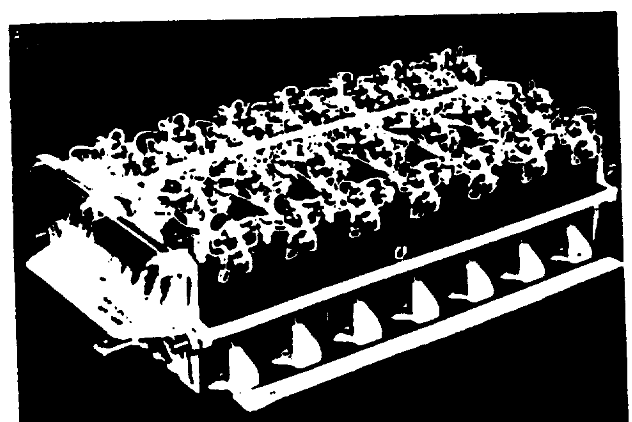


Figure 1. 12 Ah Nickel-Cadmium Battery Assembly

LIFE TEST REGIME

The life test which was performed is referred to as a semi-accelerated simulation for a geosynchronous orbiting satellite. Each eclipse season is simulated on a real time basis lasting 42 days. Each day the battery undergoes one charge/discharge cycle of 24 hours duration. The eclipse discharge period increases daily from 0.51 hours at the

* Member, American Institute of Aeronautics and Astronautic, Inc.

first eclipse day to 1.20 hours at mid-eclipse season and gradually reduces to 0.51 hours on the 42nd eclipse day. Figure 2a shows the eclipse duration as a function of the eclipse day. Since the eclipse duration changes each day the recharge time also varies from 22.80 to 23.49 hours to make up the 24 hour period.

As the eclipse time varies the depth of discharge also varies. Shorter eclipses result in lower depth of discharge while the maximum eclipse of 1.20 hours corresponds to 55% depth of discharge. Each eclipse was simulated by a constant current discharge of 5.50 A (C/2.18). Figure 2 also shows the battery depth of discharge versus eclipse time.

Recharge was performed at a high rate of 0.86 A (C/13.95) until 120% of the previous discharge ampere-hour capacity removed was returned. At that time the charge rate was reduced to the trickle rate of 0.29 A (C/41.38) until the next eclipse discharge. All charging was bisequenced on a 5 minute on, 5 minute off cycle.

To accelerate the test, the solstice seasons were shortened to 14 days as compared to 140 days a satellite sees in synchronous orbit. During the accelerated solstice season the battery was either reconditioned or subjected to a capacity determination cycle. Reconditioning was performed following odd numbered eclipse seasons by discharging the battery through a 140 ohm load connected to the battery terminals until any cell voltage dropped to 0.75 +/- 0.30 V. The battery was then recharged at 0.82 A for 40 hours followed by a trickle charge at 0.22 A until the end of the 14 day solstice period. The next eclipse season then started.

The capacity determination cycle was performed following the even numbered eclipse seasons by discharging the battery at 6.0 A until any cell voltage dropped to 0.75 +/- 0.30 V. The battery was then charged in the same manner as following a reconditioning cycle.

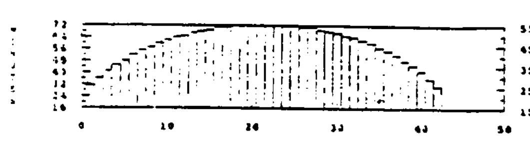


Figure 2a. Geosynchronous Orbit Eclipse Discharge Time & Battery Depth-of-discharge

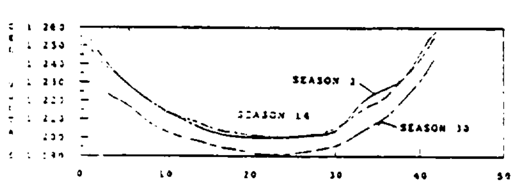


Figure 2b. End-of-discharge voltages for three seasons

The environmental conditions for the life test were as follows. The battery was mounted on a 0.5 inch thick aluminum heat sink and placed in an environmental chamber. The air circulating chamber maintained the battery at a nominal temperature of 10 degrees C, although the battery temperature was allowed to drift over the temperature range of 5 to 25 degrees C during the charge and discharge cycle. This temperature range reasonably simulates the battery temperature on a three axis stabilized spacecraft.

The test was conducted almost continuously except for short interruptions due to equipment maintenance or laboratory shutdowns.

LIFE TEST ELECTRICAL RESULTS

Equinox simulation was performed on a real time basis through the life test. Each day the eclipse time increased gradually, as it would in orbit, until the longest eclipse period of 72 minutes was reached. Several cycles were then made at 72 minutes and the discharged time was gradually shortened until a total of 42 cycles were performed, completing one equinox seasons. Figure 2b shows the end of discharge voltage of the average cell as a function of the equinox cycle. Shown on the figure are the discharge voltage trend for the 3rd (solid line)), 14th (short-dash line), and 30th (long-dash) seasons. The 3rd seasons is representative of beginning of life performance of the battery. The 14th season represents performance anticipated in orbit for a satellite whose operational life is 7 years.

Degradation from beginning of life to satellite end of life (14th season) is virtually non-existent. Both curves nearly trace each other and differences are likely due to minor temperature differences. End of discharge voltage remained above 1.200 volts through 7 equivalent years of simulated life.

Degradation from beginning of life to the end of the test was only 0.010 volts/cell. At the 30th season the longest eclipse cycle end of discharge voltage was 1.191 volts/cell average. Figure 3 indicates the trend in end of discharge voltage for the longest eclipse as a function of equinox season. The overall downward trend is very gradual. The reconditioning performed each season, either by resistive discharge or higher rate discharge for a capacity measurement is beneficial.

Figure 4 shows actual voltage plots as a functional of discharge time for the 1st, 14th, and 30th season. This data also shows little degradation in the average discharge voltage.

Capacity measurements were taken at 6.00 amperes (C/2) following every other equinox season. The measurement not only provides an indication of the total capacity of the battery but also serves to recondition the battery. Figure 5 shows

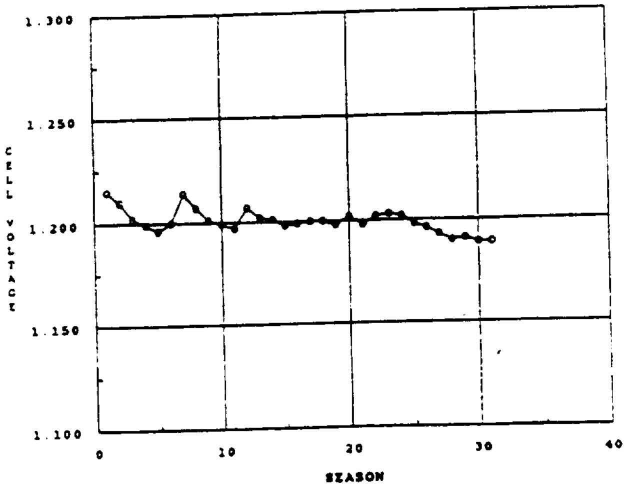


Figure 3. Minimum End of Discharge Voltage Trend vs. Equinox Season

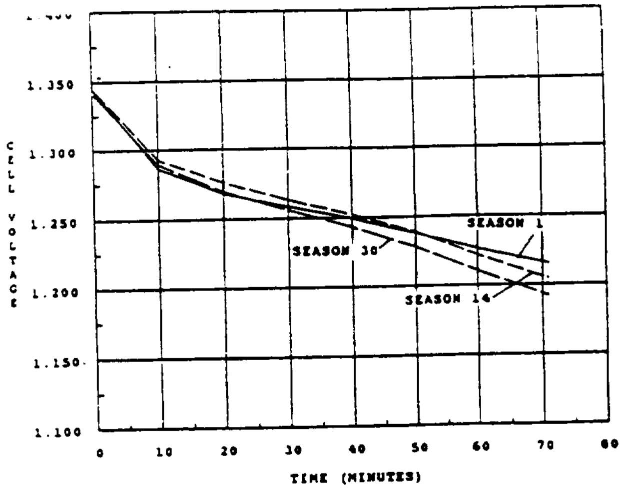


Figure 4. Eclipse Discharge Voltage Performance vs. Equinox Cycle

the results of the measurements. Although the trend line is not smooth, primarily due to test differences from season to season, one can see that the trend line is stable through 20 seasons and then begins to fall off. Even through 31 seasons the capacity stayed above the nameplate capacity of 12 Ah.

In general the discharge performance of the battery was very good throughout the test. Average and end of discharge voltage was very stable through 7 years of equivalent performance and very acceptable even at 10 years of equivalent life.

The battery eventually failed from overcharge operation. During high recharge the battery received a charge-to-discharge ratio of 1.20 before the rate was lowered to the trickle rate. All charging was done on a bisequenced basis.

Figure 6 shows the trend in peak charge voltage at the high rate. The data shows that through 20 seasons the charge voltage is below 1.500 volts/cell, a very acceptable value at 10°C. A voltage level of 1.550 volts/cell is reached at approximately 15 season. Eventually voltage above 1.60 volts/cell were reached.

To summarize, the electrical performance of the battery is very good through 7 years of equivalent life. The conditions of 55% depth of discharge, a charge-to-discharge ration of 1.20, bisequenced charging, operation at 10°C, and reconditioning prior to each season proved to be optimum operating parameters.

BATTERY CELL CHEMICAL ANALYSIS

Teardown

Two cells underwent visual inspection of their components at Ford Aerospace while two other cells underwent chemical and electrochemical analysis at Gates Energy Products, Gainesville, Fl. (formerly General Electric BBD). The following paragraphs summarize the findings:

Two representative cells removed from the battery identified as Lot 1 S/N 9 and S/N 20 were selected for destructive physical analysis (DPA). Most of the cells were bulged from internal pressure, including the two DPA cells. A typical cell stack extracted from the container is shown in Figure 7. The profile of the cell stack, container and plastic liner is shown in Figure 8. A brownish discoloration was noticed inside the liner and on the comb of the header assembly. Previous analysis of the discoloration indicated the presence of iron or iron hydroxide. Cadmium deposits were also observed at the bottom of the stack as seen in Figure 8.

The teardown started with the negative plate (No.1) from the outer side of the stack, followed by the separator and positive electrode. Figure 9 shows the typical components in the stack as they were removed from the comb of the header assembly. Both cells yielded very similar results from the DPA. The following paragraphs provide the descriptions of both cells.

Separators

The Pellon 2505 separator bag which separates the positive from the negative electrode contains varying amounts of cadmium deposits is shown in Figure 9. The upper and middle zones of the separator showed more cadmium than the lower zone possibly caused by a slightly higher current density near the electrodes tabs.

Some of the separators exhibited brownish discoloration along the area near the positive tab. These strains are likely from leached iron hydroxide developed around the positive tab. Strands of nylon from the separators were found at the upper ends of the negative electrode near the tab. These were observed in electrodes toward the middle

of the stack and are associated with cadmium migration.

Negative Plates

In general, the negative electrodes appeared dark and gray, with typical cadmium sponge growth. However, dendrites or spikes were not observed from the sponge. There was evidence of cadmium migraton and cadmium hydroxide formation on the surface of the negative plate, as seen in Figure 9. Fissures, pinholes, and pittings caused by corrosion occurred at random on the surface, as well as along the coined area of the plate.

Towards the middle of the stack, several negative plates showed cadmium migration near the tab area and superficially attached to the fibers of the separator. Evidence of cadmium deposit exists below the cell stack between the bottom and plastic liner.

The scanning electron microscope (SEM) photographs of the fractured face and flat surface shown in Figure 10, indicate the evidence of small crystal of cadmium hydroxide. These crystals are not as dense as would be expected in cells which have been extensively cycled as the DPA cells have been. This explains why the separator was not sticking to the negative electrode as has been exhibited in cells with significant cadmium migration (see following) discussion regarding separator condition).

The plate thickness measured in five different areas showed average reading of 0.032 0.033 inch representing 2.54% to 4.76% growth increase over the nominal 0.0315 inch of fresh plate. The small amount of cadmium electrode expansion may have been influenced by the presence of teflon which helps regulate the electrolyte intake. The minor thickness growth is also due to restricted growth of the active material and the absence of large crystals in the fracture face as shown in Figure 10.

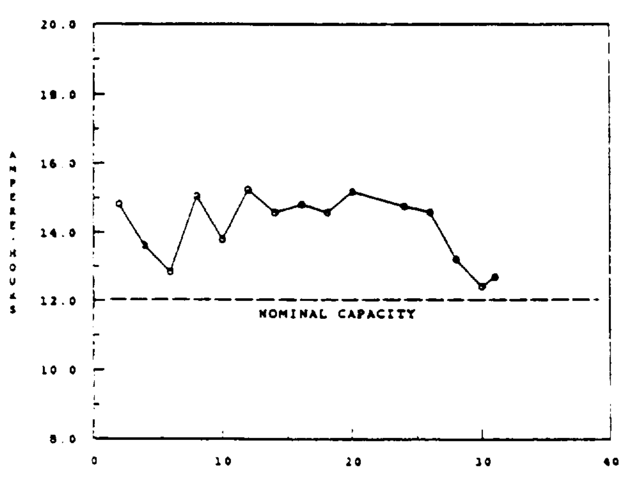


Figure 5. Battery Capacity vs. Equinox Season

Positive Plates

Irregular hairline cracks, pinholes, and growth in thickness was measured in all the plates of the two cells. The pinholes and hairline cracks observed in the cycled plates have been known to exist even in fresh plates.

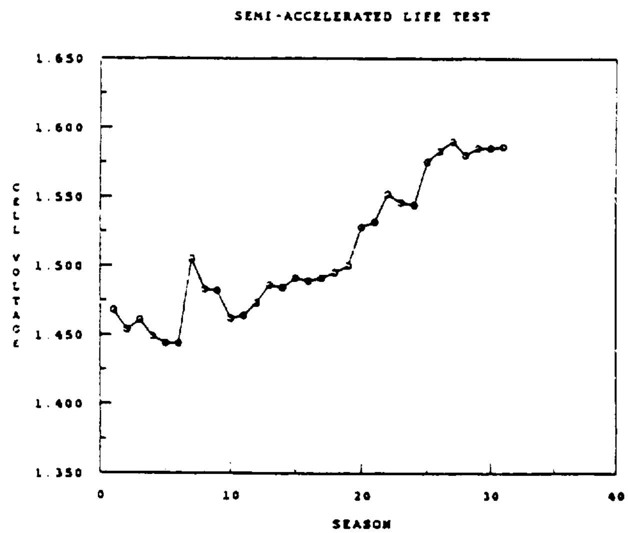


Figure 6. Peak Charge Voltage Trend vs. Equinox Season

As with the negative electrode the positive electrode was analyzed using SEM. Figure 11 shows the fractured face and flat surface of the electrode. Large nickel hydroxide crystals can be seen, possibly the effect of corrosion of the sinter structure. These large crystals are typical of vacuum impregnated nickel electrodes which have been extensively cycled. The plates were measured in five different places. Results showed an average thickness of 0.0356 inch, 32% over the nominal 0.027 inch thickness of uncycled plates. The growth is attributed to the expansion and contraction of the active material and possibly sinter corrosion, as seen in Figure 11.

Active material surfacing was observed in the plates. Dark nickel oxides were found deposited inside the separator opposite the positive plates. These materials may have been leached out by gassing or simply loose surface loading.

Though some physical changes occurred in the positive plates they evidently did not affect the cell behavior. Furthermore, some of the anomalies detected may be manufacturing defects and not related to the life test.

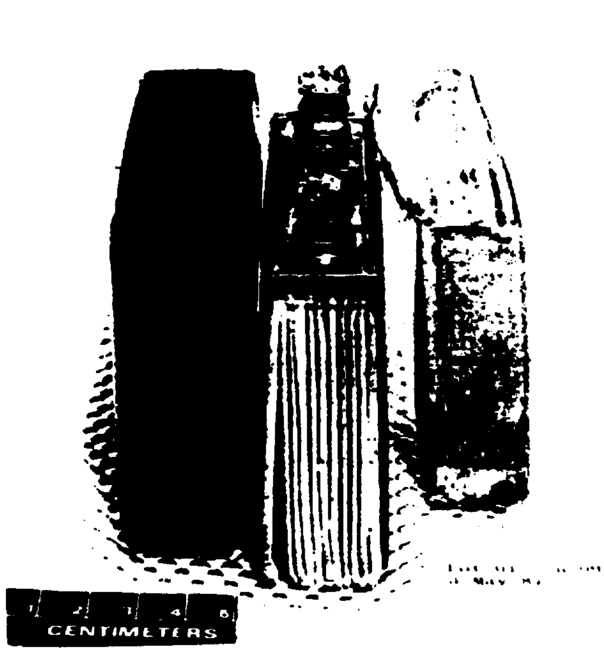


Figure 7. Post Life Test Cell Case and Stock

Figure 8. Bottom View of Cell Stack Removed from Cell Case.

<u>Electrolyte</u>

A small amount of free electrolyte was seen along the wall of the plastic liner with more found at the bottom of the stack. Since the cells were tested in the battery in upright position (terminals up) gravity may have contributed to the free electrolyte being found in the cell.

Electrolyte was less available in the outer face of the first and last negative electrodes. However, as the DPA progressed toward the middle of the stack, evidence of more available electrolyte was noticed on the face of the positive plate and separators. Likewise, a certain amount of electrolyte was retained by the cadmium sponge on the surface of the negative plate. Electrolyte uptake is regulated in teflonated negative plate.

<u>Battery Chemical Analysis</u>

Chemical and electrochemical properties, were analyzed on two cells at Gates Energy Products (formerly General Electric Co. BBD). Results were compared with uncycled cells to evaluate the shift of negative overcharge protection, to monitor the amount of precharge and capacity utilization.

The negative electrode electrochemical utilization was found to be 79.2% at end of life. All cells lost their overcharge protection which increased the cell internal pressure ultimately resulting in the battery failure. The loss of overcharge protection also increased the amount precharge from 4.71 Ah beginning of life test to 11.65 Ah at the end of the life test.

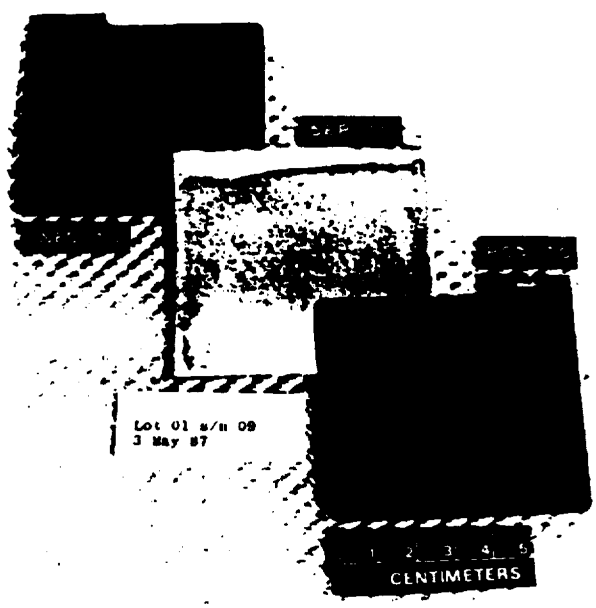


Figure 9. Typical Cell Stack Components Following Life Test.

Figure 12 compares the beginning of life electrode balance with the end of life balance. There was also 4.46 Ah (residual) loss due to migration of cadmium. About 10.5 % went to the positive electrodes. The positive con-

tained a small amount of cadmium as antipolar mass. A total of about 3.0% cadmium was attached to the separator and others considered as residue. Cadmium deposited outside and at the bottom of the cell stack is considered residue. The 32.53 Ah total negative cadmium per cell is comparable with the baseline data from the uncycled cells.

The positive electrodes exhibited an average capacity of 14.66 Ah discharged to 0.5 volt and 16.42 Ah to 0.0 volt when completely discharge through a resistor. Chemical analysis indicated 19.69 Ah total positive showing that the positive has 83.4% utilization.

Analysis of the electrolyte indicated 7.25% potassium carbonate which is considered low for the equivalent duration of a 15.5 year life test. The condition of the separators which remained sound as observed during the cell DPA, supports the presence of minimal carbonate due to separator degradation.

Figure 10. SEM Photograph of Negative Electrode Fracture

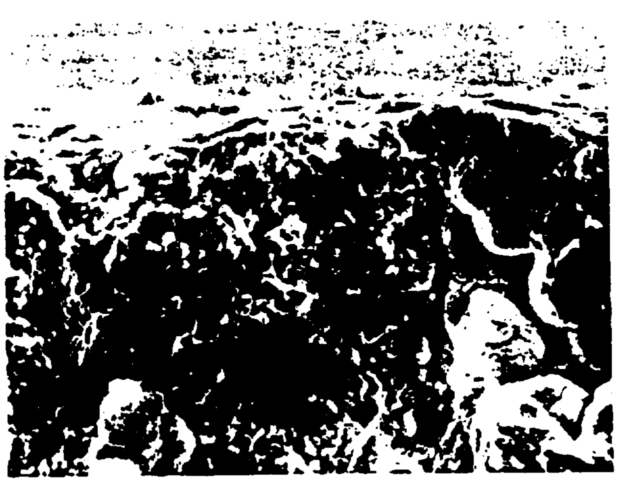


Figure 11. SEM Photograph of Positive Electrode Fractured Face

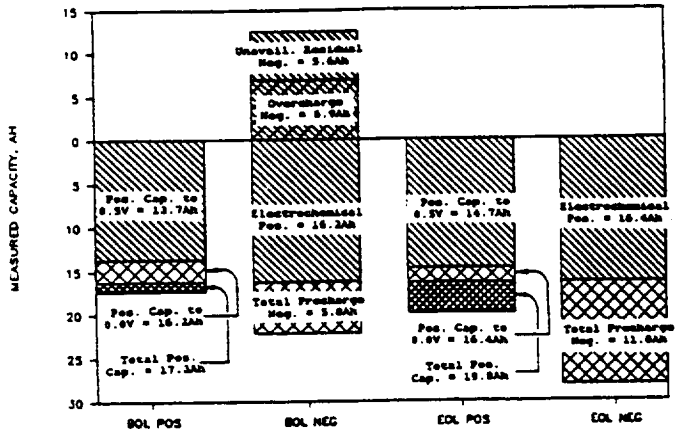


Figure 12. Relative Electrode Electrochemical Balance.

CONCLUSION

The 12 Ah Ni-Cd battery assembly successfully completed its life test verifying is design life of 7 years. In total, 15.5 years of equivalent synchronous orbit cycle life was demonstrated. Electrical performance was virtually undegraded through 7 years of performance. Chemical and electrochemical characteristics at end of life were predictable. The data presented here and in the reference papers fully supports the qualification of the Ford Aerospace 12 Ah Ni-Cd battery design for most any geosynchronous orbit spacecraft requiring 7 years of operational life.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the dedication of R. Quiroz, B. Ridout, and R. Hudak in performing this test and compiling the test data over the 5 years which the test was conducted.

REFERENCES

1. "12 Ah Nickel-Cadmium Battery for Multiple Satellite Applications", C. W. Koehler, Proceedings of the 16th Intersociety Energy Conversion Engineering Conference, 1981, p. 195.

2. "Qualification and Life Test Results for the Multiple Satellite 12 Ah Nickel-Cadmium Battery", C. W. Koehler, Proceedings of the 17th Intersociety Energy Conversion Engineering Conference, 1982, p. 721.

"THE AEROSPACE NiCd CELL SEPARATOR QUALIFICATION PROGRAM: UPDATE"

ROBERT FRANCIS

The Haag/Francis paper was presented by Robert Francis of Aerospace Corp. The title was "The Aerospace NiCd Cell Separator Qualification Program: Update".

The purpose of testing was to qualify the new Pellon 2536 separator material (Francis [Figure 2]). Regarding the pack test schedule, they were not able to start the characterization tests because of schedule delays (Francis [Figure 5]). The 35 amp-hour cells had failed the acceptance tests at 86 degrees F at the vendors (Francis [Figure 6]). At Crane they again were tested and again had failure due to high charge voltages. During recertification it was found that at 1400 cycles the voltage on one of the cells in the 34 AH packs was decreasing compared to the others. Test procedure was then coordinated with NRL. The thought was that the new separator was not optimized in the present cells.

Simultaneous test parameter changes on 2505ML and 2536 separator packs was done at NWSC/Crane. The same changes were made for both cells as listed in Test Parameter Changes (Francis [Figure 8]). Changes were initiated at around 1600 cycles, and this was very premature. Every possible parametric change was done to improve LEO performance but nothing helped using new V/T - limits or charge rates, charge voltages responded for 50 cycles or less. Francis [Figure 16] shows LEO cell pack status as of 10/21/87. In the LEO 50 amp-hour ten-cell packs at 20 degrees C, high temperature variations were noted and pack temperature changed to 0 degrees C after about 950 cycles. The graphs for geosynchronous packs with 2536 show that voltage is lower at mid-season, but there is good capacity utilization correlation between the old and the new pellon separators.

There will be a report issued the middle of calendar year 1988.

Q. _____? : What's the voltage dispersion curve? Did you recondition? Did the voltages come back together?

A. Yes, we had standard reconditioning down to C/2. We charged at C/20 for 32 hours and saw improvements in short cycles (< 50). We later included an overcharge for 48 hours. We still had little change in dispersion.

Q. Morrow(GSFC): Was there a few mv change?

A. None.

Q. Methlie (U.S. Govt): Compared to early cells from the seventies, both of these cells look bad. Is that right?

A. Yes, something is causing this. It appears to be the separators.

Q. Possibly, better data are available from the old cells.

Q. Gaston (RCA): We have a new and an old separator cell test--we have seen no improvements with the new cell separator.

A. Yes, we agree.

UPDATE ON SEPARATOR QUALIFICATION PROGRAM FOR AEROSPACE NICD CELLS

C. C. BADCOCK, M. J. MILDEN, AND R. W. FRANCIS
THE AEROSPACE CORPORATION
EL SEGUNDO, CALIFORNIA

R. L. HAAG AND S. HALL
NAVAL WEAPONS SUPPORT CENTER
CRANE, INDIANA

1987 NASA/GSFC
BATTERY WORKSHOP

FIGURE 1. FRANCIS

INTRODUCTION

- PURPOSE OF TEST
  - QUALIFY NEW PELLON 2536 SEPARATOR MATERIAL
  - CONDUCT BOTH REAL TIME AND ACCELERATED LIFE TESTING
- BACKGROUND
  - MANUFACTURE OF AEROSPACE QUALIFIED PELLON 2505 ML DISCONTINUED IN 1976
  - CONDUCT JOINT AIR FORCE/NAVY SPONSORED PROGRAM
  - SIMULTANEOUS TESTING OF 2505ML AND 2536 SEPARATORS AT NWSC/CRANE
  - CYCLE LIFE TESTING STARTED DEC 1985
  - PREVIOUS REPORTS AT 1985 GSFC BATTERY WORKSHOP AND 21ST IECEC, 1986
- UPDATE
  - PERFORMANCE TRENDS AND TEST PARAMETER CHANGES
  - PACK STATUS AND CELL FAILURES
- DISCUSSION
- PLANS

FIGURE 2. FRANCIS

TEST MATRIX

				2505 ML SEPARATOR				2536 SEPARATOR			
ORBIT	DOD % ACTUAL	CHARGE CONTROL	TEST TEMP °C	50AH	34AH	35AH	26.5AH	50AH	34AH	35AH	26.5AH
LEO	25	V/T TAP	0		5		5	5	5		5
LEO	40	V/T TAP	20		10		9	10	10		9
GEO ACCEL	75	V/T TAP	0	5		5		5		5	
GEO ACCEL	75	V/T TAP	20	10		10		10		10	

FIGURE 3. FRANCIS

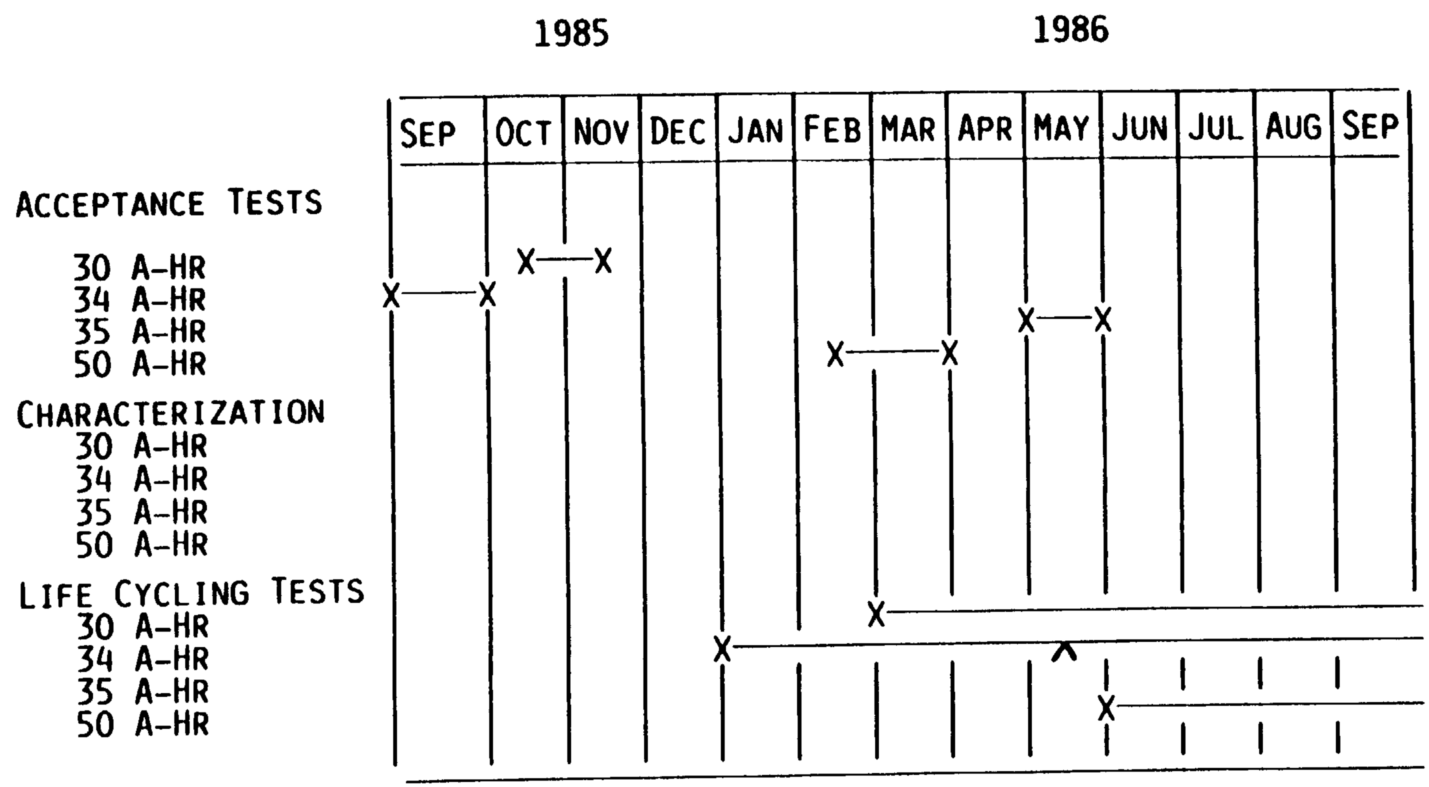
LIFE CYCLE DETAILS

TEST	CAPACITY NAMEPLATE	CAPACITY EST. ACTUAL*	CURRENT DISCHARGE	CURRENT CHARGE	V/T CURVE	C/D RANGE
LEO, 25%, 0°C	26.5AH	30.5AH	13.6A	C/3(10.2A)	6	1.00- 1.08
	34	41.5	18.5	C/2(20.75)	6	1.00- 1.08
	50	54.4	24.3	C/3(18.1)	6	1.00- 1.08
LEO, 40%, 20°C	26.5AH	30.0AH	21.4A	C/2(15.0A)	6	1.00- 1.08
	34	42.0	30.0	C/2(21.0)	6	1.00- 1.08
0°C	50	52.4	37.4	C/2(26.2)	6	1.00- 1.08
						TAPER CURRENT
GEO, 75%, 0°C	35AH	37AH	23.1A	C/10 (3.7A)	6	0.65 -0.3A
	50	54.6	34.6	C/10 (5.5)	6	0.85 -0.5
GEO 75%, 20°C	35AH	37AH	23.1A	C/10 (3.7A)	6	0.65 -0.3A
	50	52.4	32.7	C/10 (5.2)	6	0.85 -0.5

*DOD BASED ON ACTUAL CAPACITY (CONTRIBUTES A SMALL ACCELERATION)

FIGURE 4. FRANCIS

PACK TEST SCHEDULE



^ 1ST TIME TEST PLAN DEVIATION REQUIRING NON-PLAN INTERVENTION (CYCLE 1613)

FIGURE 5. FRANCIS

UPDATE

- 35 AH CELLS FAILED ACCEPTANCE TEST AT 86°F (30°C)
  - A/T REPEATED AT NWSC/CRANE AND FAILED HIGH TEMPERATURE CHARGE VOLTAGE LIMIT AGAIN
  - A/T REPEATED AGAIN AT NWSC/CRANE ALLOWING FOR CHARGE VOLTAGE SIGNATURE AND FAILED AGAIN
  - CELLS FAILED A THIRD TIME FOLLOWING CELL VENDOR RECOMMENDATIONS TO LOWER CHARGE RATE
  - CELLS SENT BACK TO GEO WITH THEIR DISPOSITION UNDER DISCUSSION

- OTHER THREE-CELL TYPES ARE NOW UNDER LEO TEST
  - INITIALLY ENCOUNTERED CHARGE VOLTAGE DISPERSIONS IN LOW TEMPERATURE LEO CYCLING
  - V/T LIMITS AND CHARGE CURRENT RATES CHANGED TO BRING VOLTAGE LEVELS IN LINE
  - NWSC/CRANE IMPLEMENTED A PACK STABILIZATION SEQUENCE SUGGESTED BY VENDOR
  - PACKS RESPOND BUT ONLY IN THE SHORT TERM

FIGURE 6. FRANCIS

RECERTIFICATION
LIFE CYCLING PERFORMANCE
Pack: 334B Manf: GE 34 AH
Orbit: LEO Temp(C): 0 DOD(%): 25
Discharge(Amp/Hrs): 18.5/.56 Charge(Amp/Hrs): 20.0/1.12
Initial Voltage Limit (V/C): 1.480 Vt Level: 6
Cell Design: New Pellon (CALCULATED 41.5 A/H)

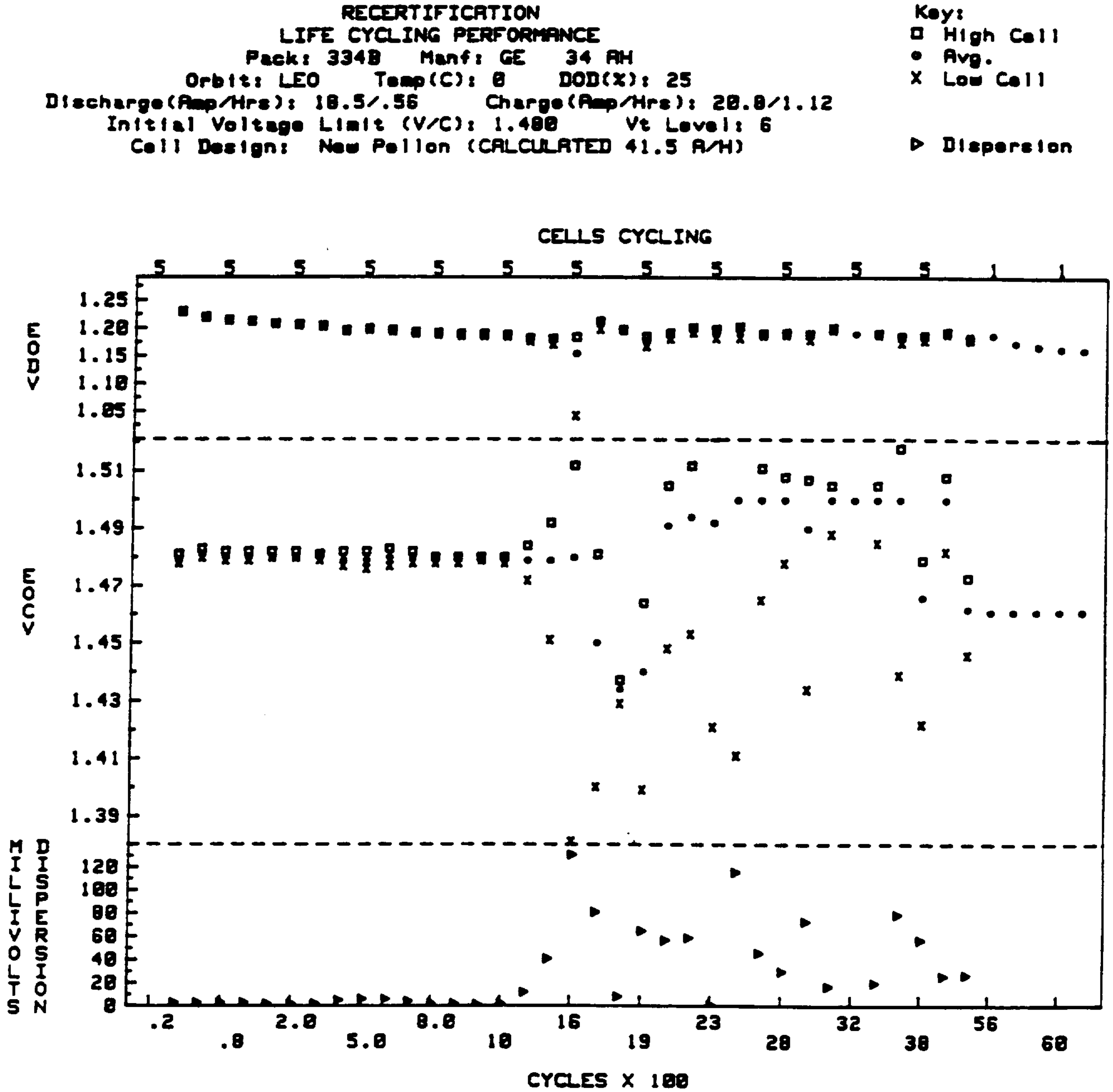


FIGURE 7. FRANCIS

LIST OF TEST PARAMETER CHANGES

INITIAL CONDITIONS

NAMEPLATE CAPACITY: 34AHr
SEPARATOR: 2536
TEMPERATURE: 0°C
DOD: 25%
V/T LEVEL: 6

CHANGE/COMMENTS	LEO CYCLE #
VT 5.5 (1.470 V/C) I=14A	1613-1640*
VT 4.5 (1.450 V/C)	1645-1684*
VT 6 (1.434 V/C) I=20.75 TEMP 20°C	1688-1882
VT 4 (1.440 V/C) I=14A TEMP 0°C	1883-1914*
VT 6.5 (1.490 V/C)	1916-2235*
I=10A	2238-2271
VT 7 (1.500 V/C)	2272-2286*
I=12A	2289-2359*
I=14A	2361-2714
I=17A	2715-2814
VT 6.5 (1.490 V/C)	2815-2859*
VT 7 (1.500 V/C)	2861-2918
I=20.75	2921-3493*
VT 7 (1.477 V/C) TEMP 10°C	3495-3540
VT 6.5 (1.467 V/C)	3541-3846*
	3847-3908*
VT 7 (1.50 V/C) TEMP 0°C SPLIT WITH SISTER PACK	3979-4011
CELL #5 REMOVED	4013
VT 4 (1.440 V/C)	4314
VT 5 (1.460 V/C)	4382
CELL #3 REMOVED	4508
CELL #1 REMOVED	4755
CELL #4 REMOVED	4771

* PACK RECONDITION AFTER THIS CYCLE

FIGURE 8. FRANCIS

LIST OF TEST PARAMETER CHANGES

INITIAL CONDITIONS

NAMEPLATE CAPACITY: 34AHr
SEPARATOR: 2505
TEMPERATURE: 0°C
DOD: 25%
V/T LEVEL: 6

CHANGE/COMMENTS	LEO CYCLE #
VT 5.5 (1.470 V/C) I=14A	1622-1651*
VT 4.5 (1.450 V/C)	1655-1695*
VT 6 (1.434 V/C I=20.75 TEMP 20°C	1700-1892
VT 4 (1.440 V/C) I=14A TEMP 0°C	1893-1925*
VT 6.5 (1.490 V/C)	1927-2249*
I=10A	2251-2284
VT 7 (1.50 V/C)	2285-2300*
I=12A	2302-2373*
I=14A	2375-2729
I=17A	2730-2829
VT 6.5 (1.490 V/C)	2830-2873*
VT 7 (1.50 V/C)	2875-2932*
I=20.75	2935-3508*
VT 7 (1.477 V/C) TEMP 10°C	3510-3555
VT 6.5 (1.467 V/C)	3556-3872*
	3873-3932*
VT 7 (1.50 V/C) TEMP 0°C SPLIT WITH SISTER PACK	4004
CELL 5 REMOVED	6241

* PACK RECONDITION AFTER THIS CYCLE

FIGURE 9. FRANCIS

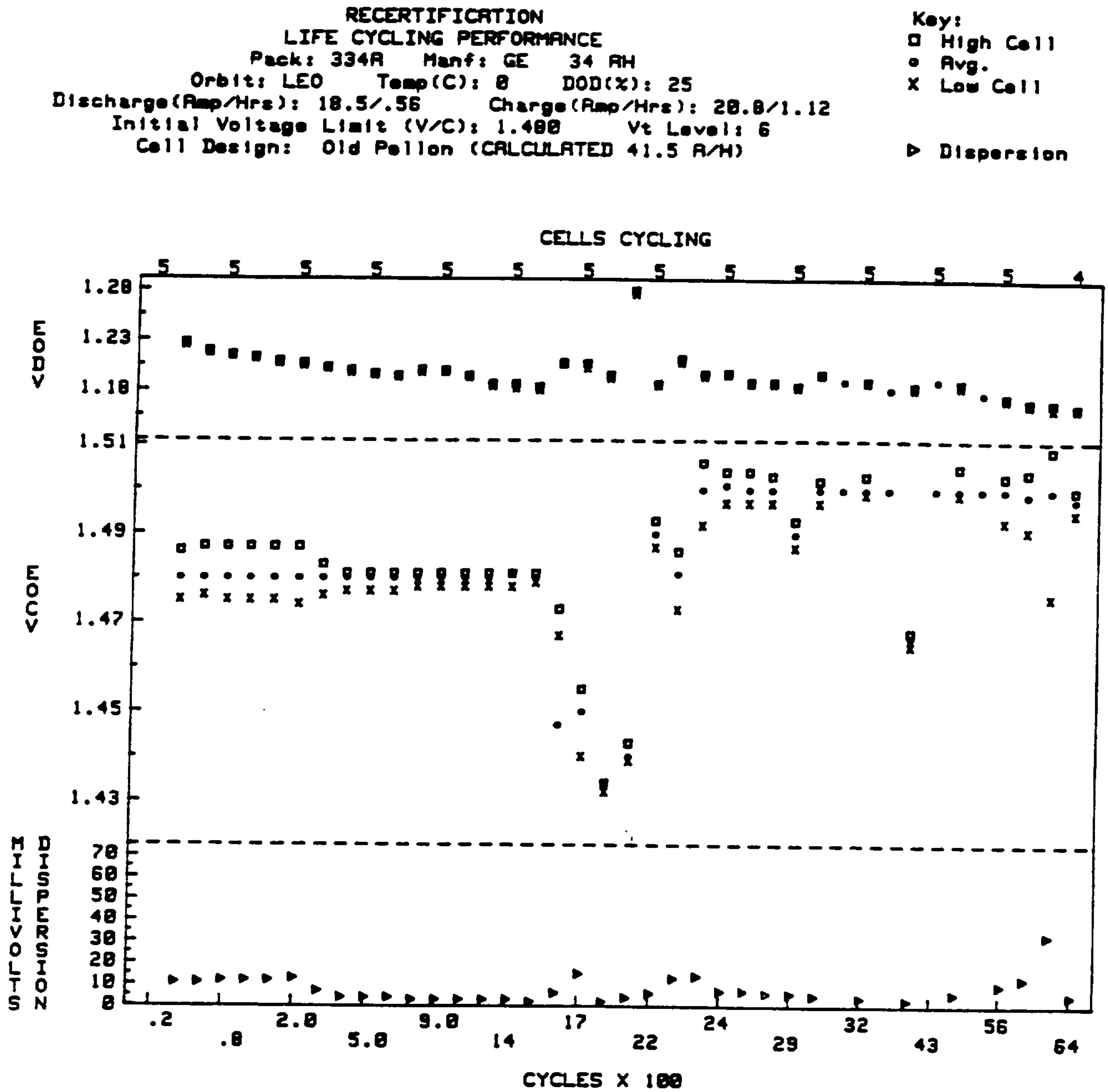


FIGURE 10. FRANCIS

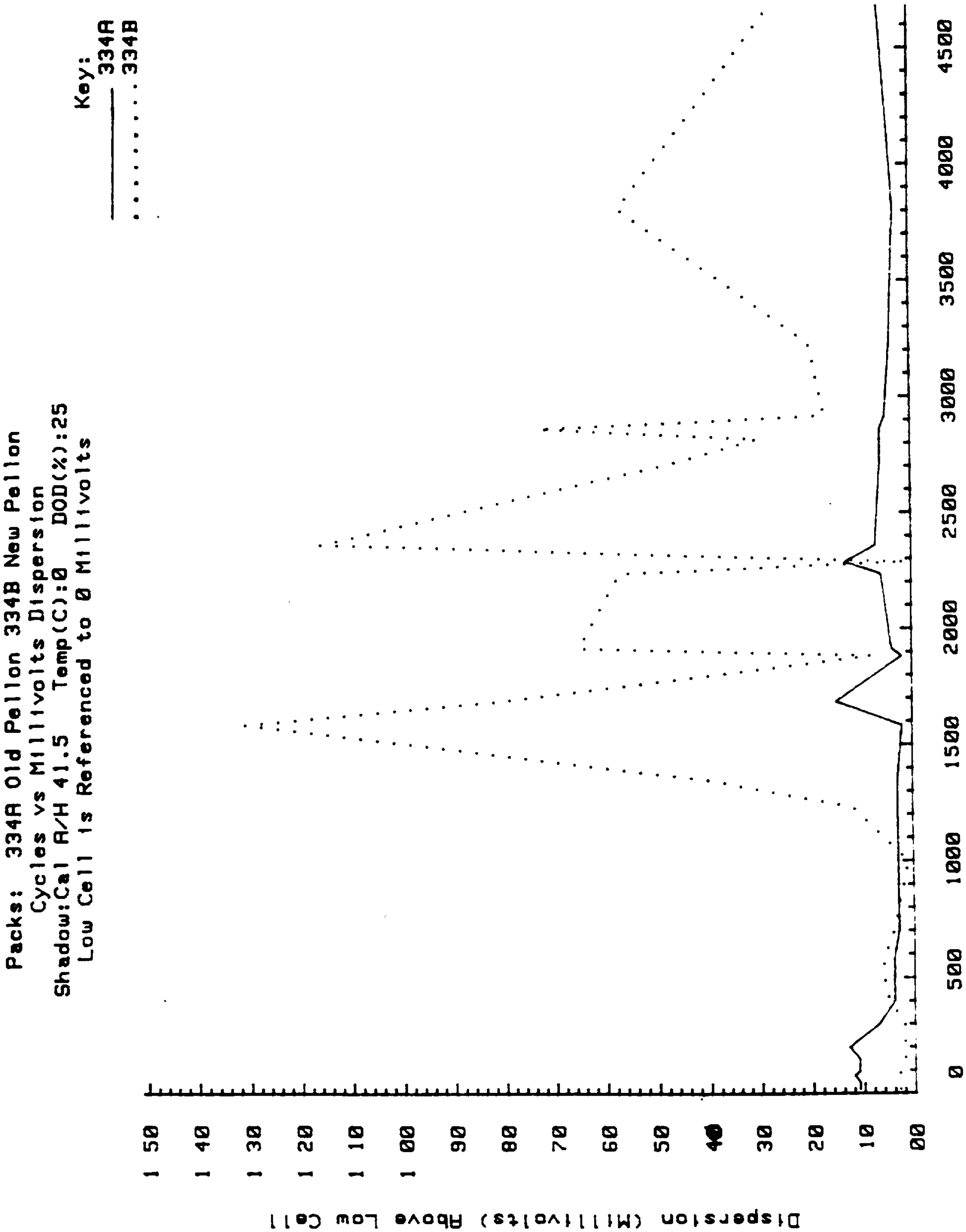
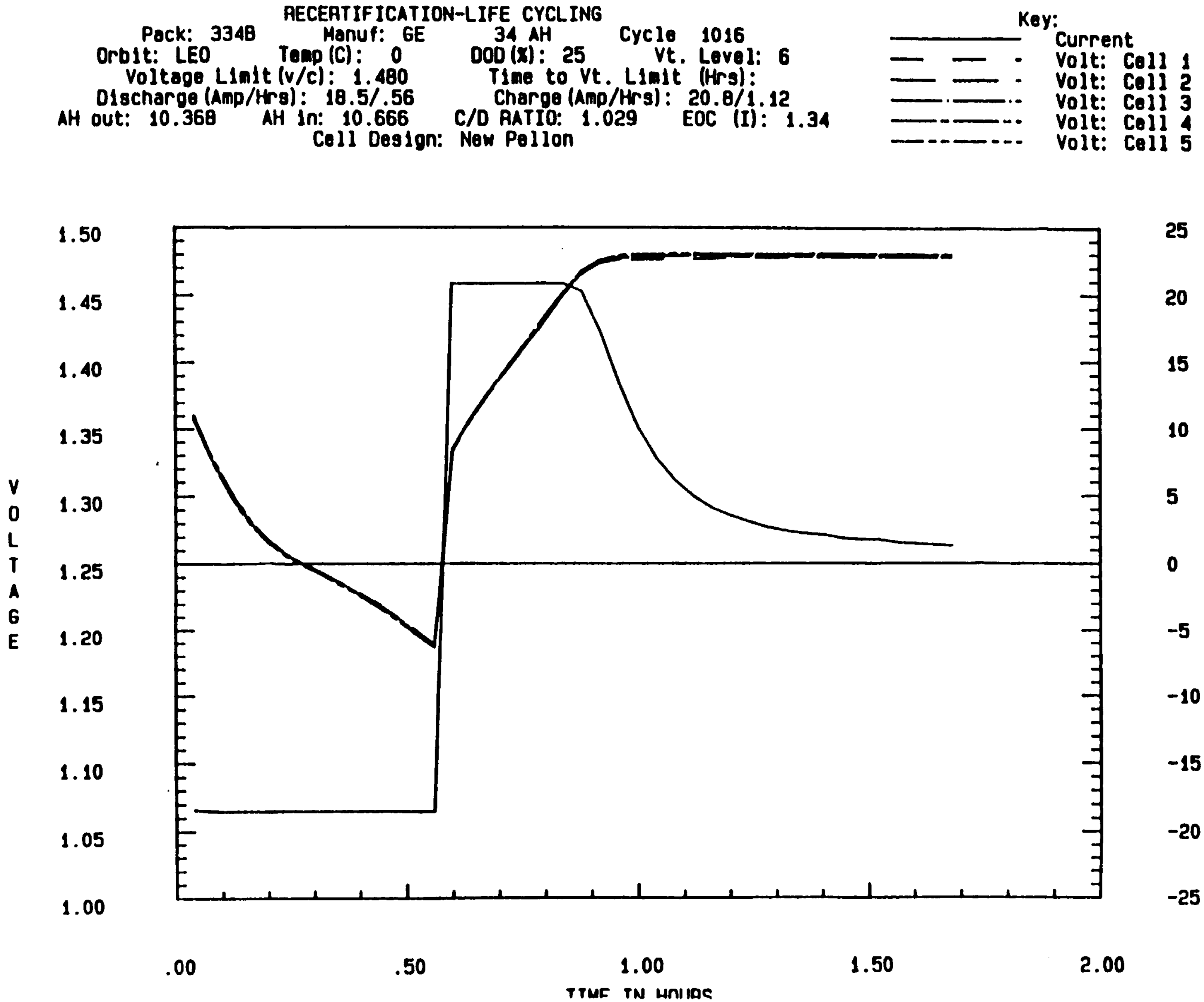


FIGURE 11. FRANCIS



RECERTIFICATION-LIFE CYCLING
Pack: 334B
Manuf: GE
34 AH
Cycle 1016
Orbit: LEO
Temp (C): 0
DOD (%): 25
Vt. Level: 6
Voltage Limit (v/c): 1.480
Time to Vt. Limit (Hrs):
Discharge (Amp/Hrs): 18.5/.56
Charge (Amp/Hrs): 20.8/1.12
AH out: 10.368
AH in: 10.666
C/D RATIO: 1.029
EOC (I): 1.34
Cell Design: New Pellon
Key:
Current
Volt: Cell 1
Volt: Cell 2
Volt: Cell 3
Volt: Cell 4
Volt: Cell 5
VOLTAGE
1.50
1.45
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
CURRENT
25
20
15
10
5
0
-5
-10
-15
-20
-25
.00
.50
1.00
1.50
2.00

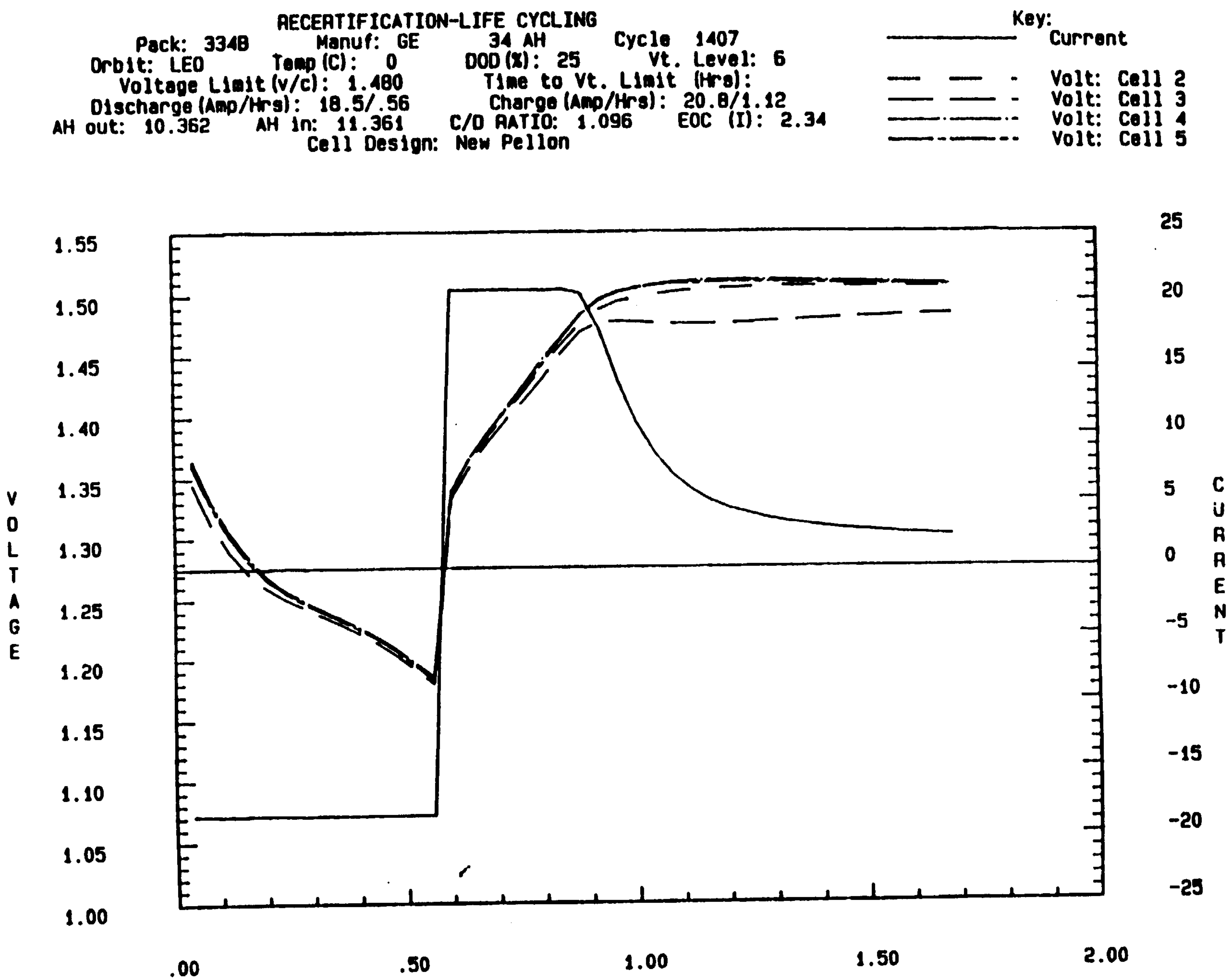


FIGURE 13. FRANCIS

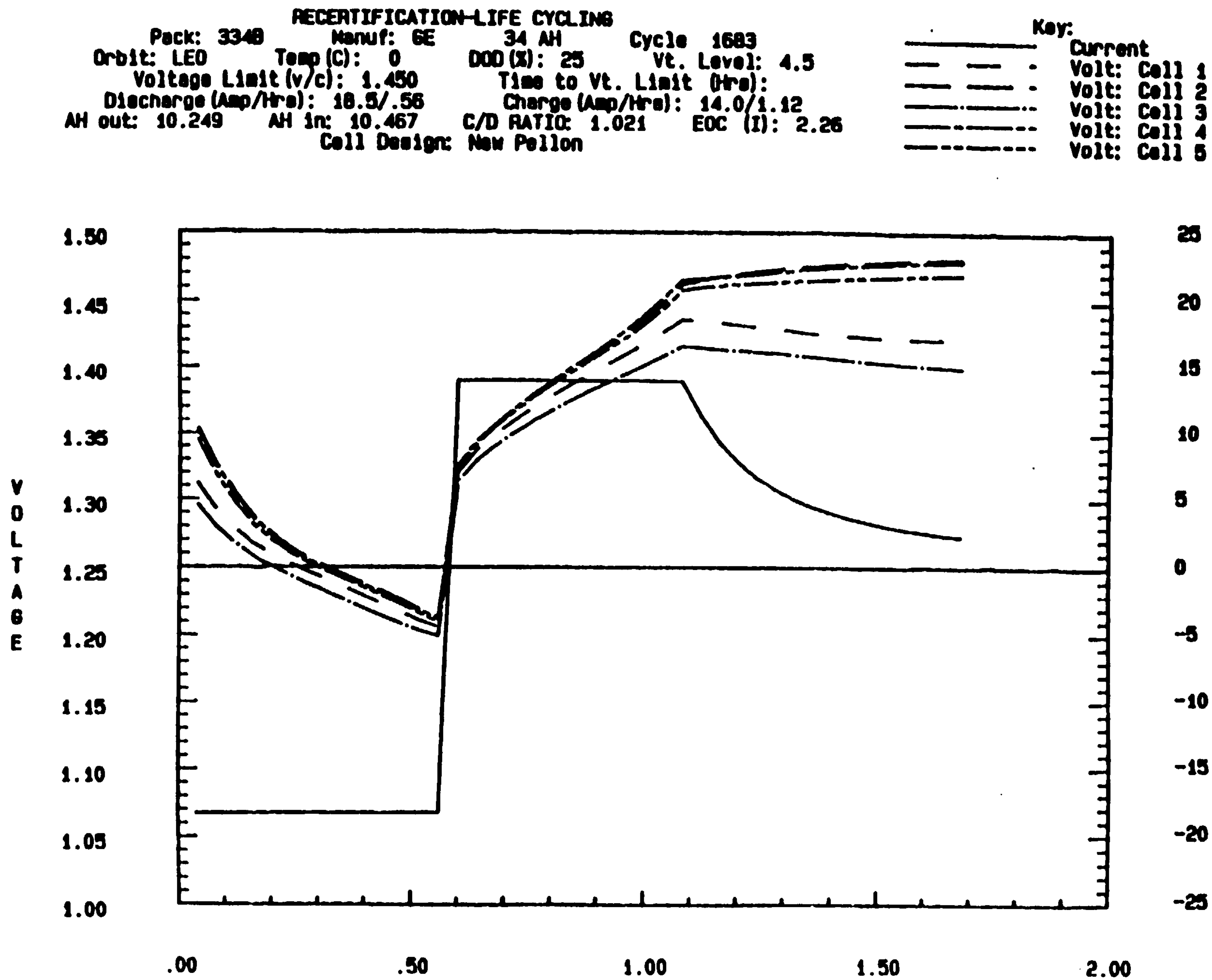
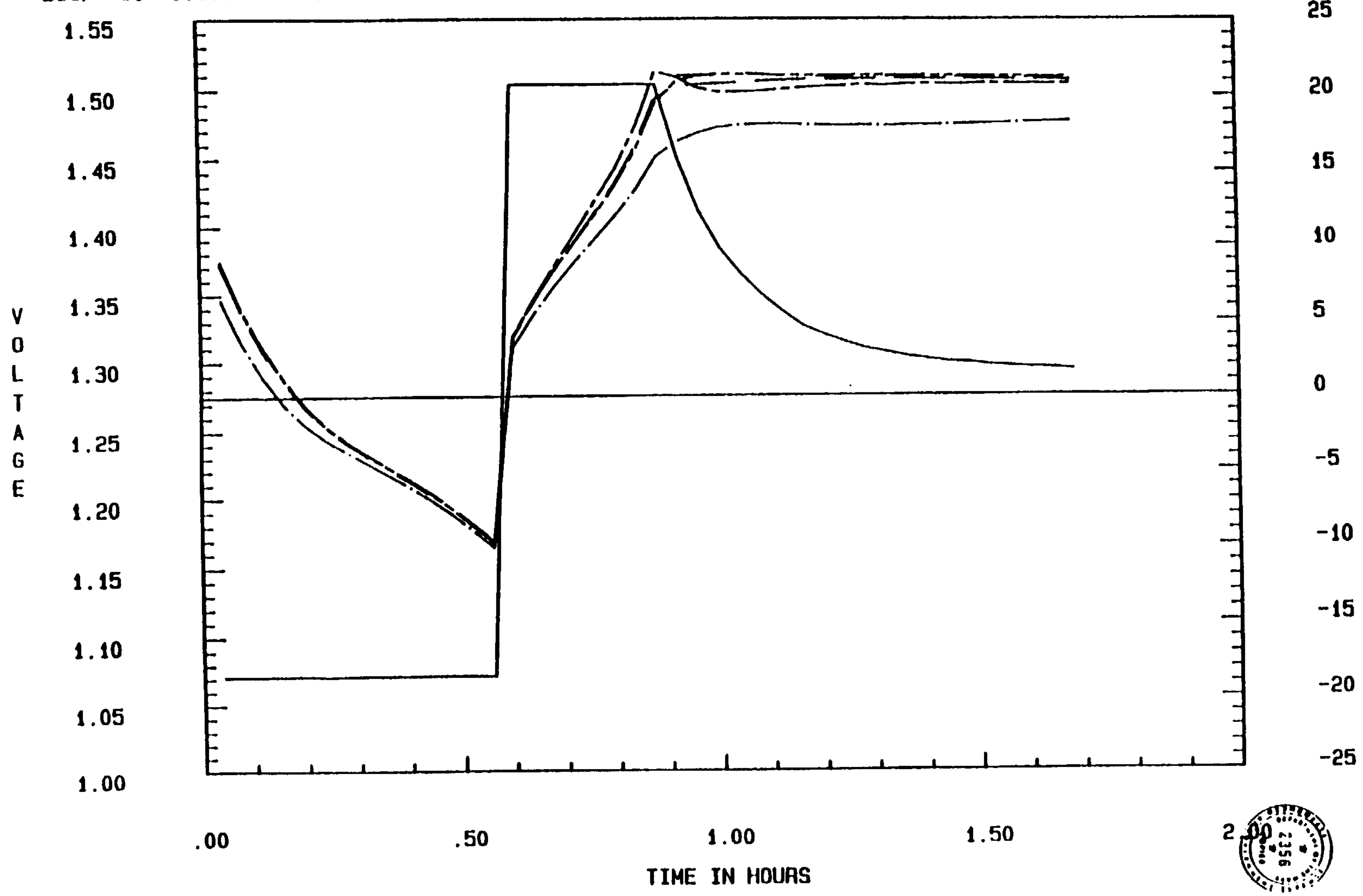


FIGURE 14. FRANCIS

START OF CYCLE: 10/ 8/87 RECERTIFICATION-LIFE CYCLING
Pack: 334A Manuf: GE 34 AH Cycle 6111
Orbit: LEO Temp(C): 0 DOD(%): 25 Vt. Level: 7
Voltage Limit(v/c): 1.500 Time to Vt. Limit (Hrs):
Discharge(Amp/Hrs): 18.5/.56 Charge(Amp/Hrs): 20.8/1.12
AH out: 10.373 AH in: 10.827 C/D RATIO: 1.044 EOC (I): 1.66
Cell Design: Old Pellon

Key:
Current
Volt: Cell 1
Volt: Cell 2
Volt: Cell 3
Volt: Cell 4
Volt: Cell 5

EOD: C1= 1.169 C2= 1.169 C3= 1.164 C4= 1.167 C5= 1.168 AV= 1.168 T3= .550 AMB=-1.360
EOC: C1= 1.507 C2= 1.506 C3= 1.476 C4= 1.504 C5= 1.509 AV= 1.500 T3=-1.170 AMB=-1.300



C.4

- LEO CELL PACK PRESENT STATUS*

5-CELL PACKS

NAMEPLATE CAPACITY	SEPARATOR TYPE	FIRST CYCLE TEST DEVIATION	CELLS IN PACK	V/T LIMIT	CYCLE NO.
26.5AH	2505ML	3576	5	6.5	7779
26.5	2536	--	5	6.5	7787
34	2505ML	5991	4	7	6267
34	2536	1583	1	5	6208
50	2536	4502	1	5.5	6624

10-CELL PACKS

NAMEPLATE CAPACITY	SEPARATOR TYPE	FIRST CYCLE TEST DEVIATION	CELLS IN PACK	V/T LIMIT	CYCLE NO.
26.5AH	2505ML	5929	9	7.5	7868
26.5	2536	7197	9	7.5	7853
34	2505ML	--	10	7.5	8340
34	2536	6128	5**	7.5	8285
50	2536	2592	0	7	5236

*AS OF 10-21-87

**CELLS REMOVED DUE TO LOW EODV

FIGURE 16. FRANCIS

- LEO PERFORMANCE TRENDS AND ACTIONS TAKEN
  - CELL IMPENDING FAILURES AND SUBSEQUENT TEST PARAMETER CHANGES INVOKED TO PROLONG CYCLING
    - RECONDITIONING CYCLE
    - DECREASE V/T-LIMIT
    - DECREASE CHARGE RATE
    - INCREASE CHARGE RATE
    - INCREASE V/T-LIMIT
  - DECISION THEN MADE TO ALLOW LEO PACKS TO CYCLE UNTIL A CELL FAILED BY
    - DISCHARGE TO BELOW 1.00V
    - DEVIATION GREATER THAN 50MV ON CHARGE
  - CORRECT IMBALANCE BY REMOVING LOW VOLTAGE CELL
  - PERFORMANCE CHARACTERISTICS UNDER EVALUATION AND DISCUSSION WITH CELL VENDOR

FIGURE 17. FRANCIS

- DISCUSSION (LEO PERFORMANCE TRENDS)
  - SEPARATOR
    - MORE CELLS IN NEW SEPARATOR PACKS HAVE FAILED
    - 2536 SEPARATOR MAY NOT BE DIRECT CAUSE OF FAILURE
    - CELLS WITH 2505ML SEPARATOR ARE STARTING TO EXHIBIT SAME DEVIATION IN CHARGE VOLTAGE
    - DESIGN PARAMETERS FOR NEW SEPARATOR CELLS MAY NOT BE OPTIMIZED
    - DPA'S WILL BE INITIATED TO EVALUATE CELL SEPARATOR/ELECTRODE CONDITION
  - CELL PACKS
    - ALL CELL TYPES SHOW VOLTAGE DISPERSION INDEPENDENT OF SEPARATOR USED
    - ELECTRODE PERFORMANCE MAY BE CONTRIBUTING FACTOR
    - ONSET OF VOLTAGE DISPERSION POSSIBLY RELATED TO NUMBER OF CELLS PER PACK

FIGURE 18. FRANCIS

- DISCUSSION (GEO PERFORMANCE TRENDS)
  - 50AH NAMEPLATE CAPACITY CELLS
  - 2505ML AND 2536 SEPARATOR COMPARATIVE PACKS
  - PACK TESTING
    - O 5-CELL 0°C AND 10-CELL 20°C PACKS
    - O 75% MAXIMUM DOD AT MID-SEASON
    - O ECLIPSE PROFILE IS 41 SHADOW DAYS PER SEASON
    - O C/10 CHARGE TO V/T TAPER CURRENT CONTROL
  - TESTING STATUS
    - O ALL 50AH GEO PACKS ARE IN SHADOW SEASON NO. 8*
  - DISCUSSION
    - O 20°C PACKS EXHIBIT HIGH (> 1.0A) END-OF-TAPER CHARGE CURRENTS
    - O 50AH CELLS HAVE LOW TEMPERATURE DESIGN ELECTRODES

*AS OF 10-21-87

FIGURE 19. FRANCIS

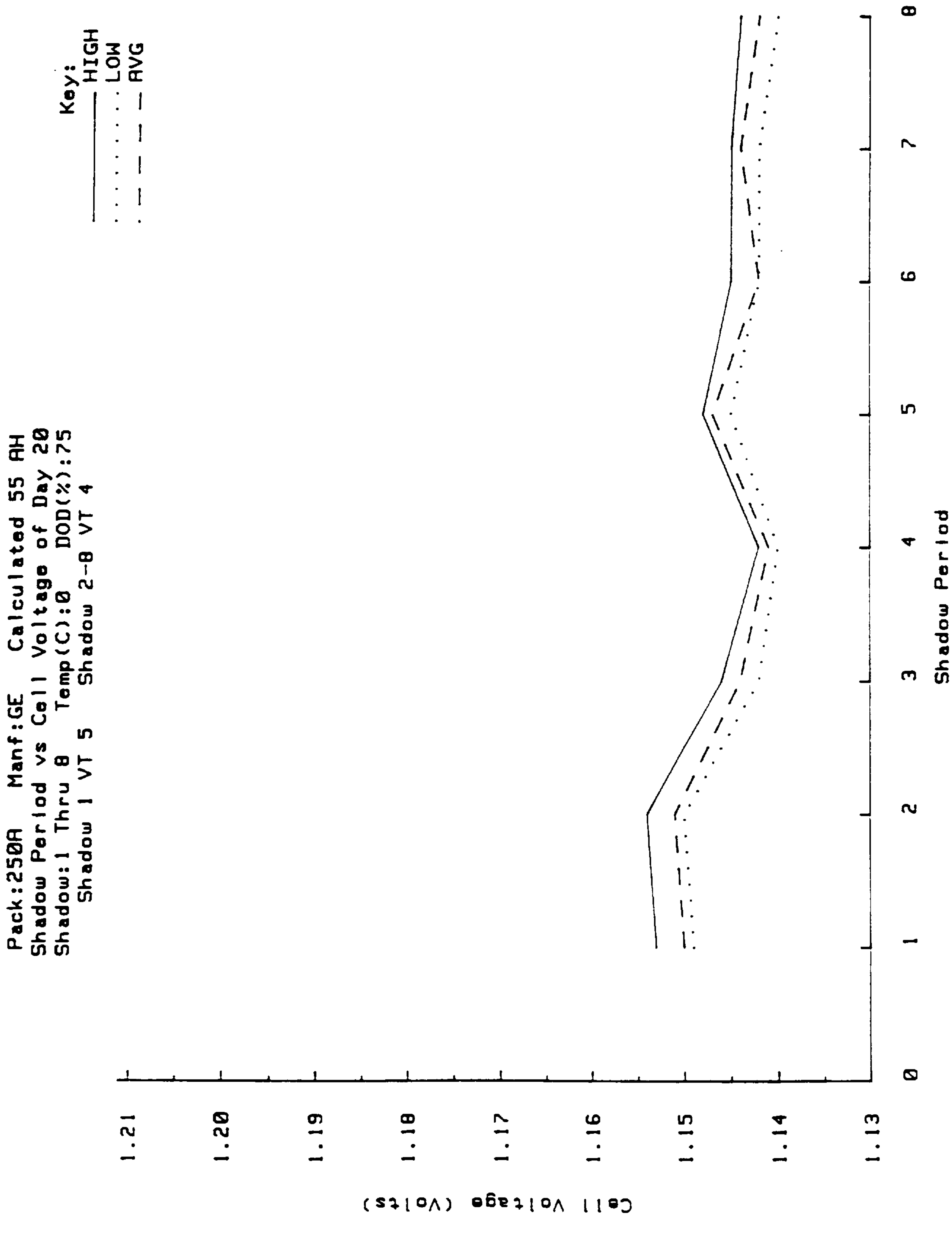


FIGURE 20. FRANCIS

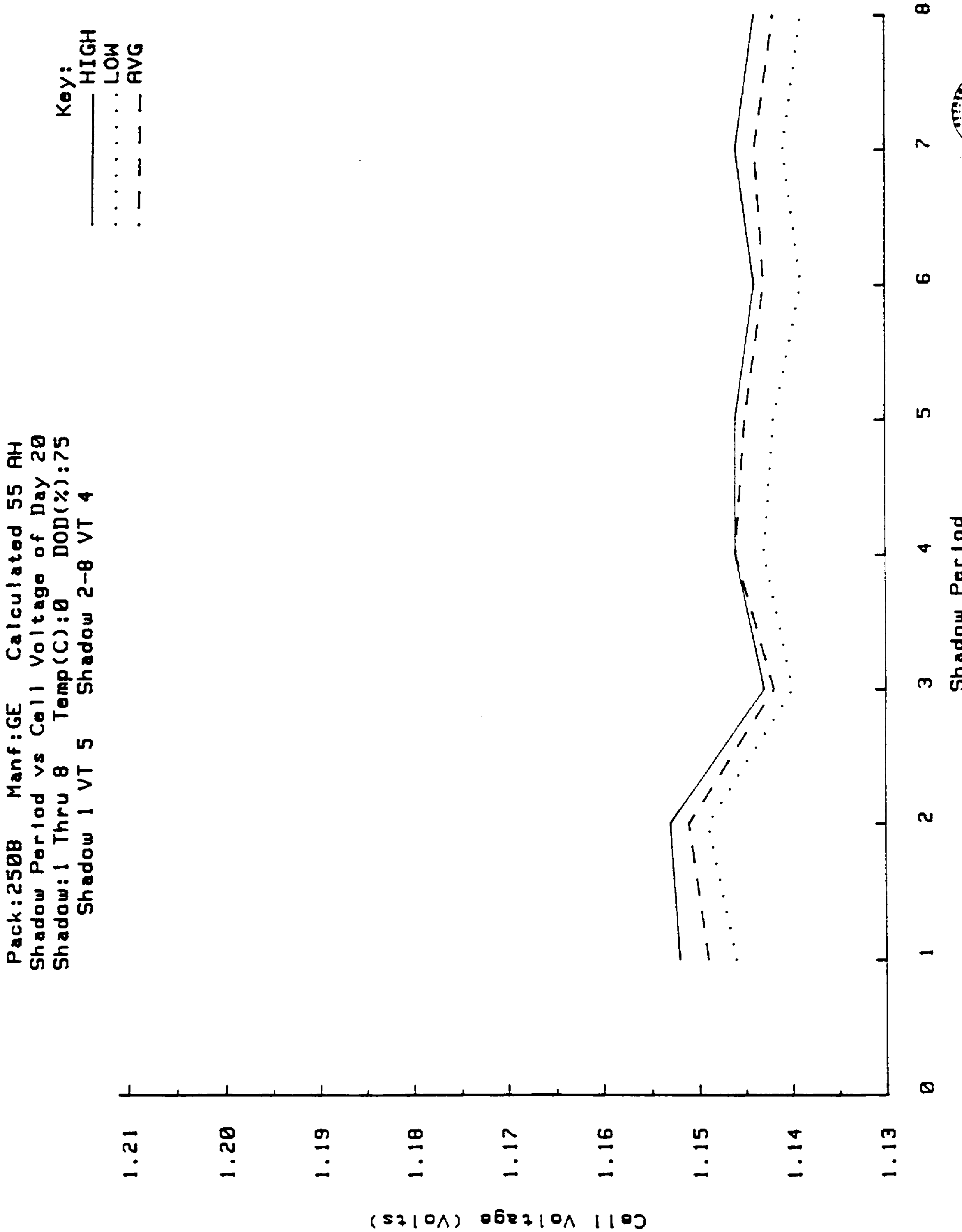


FIGURE 21. FRANCIS

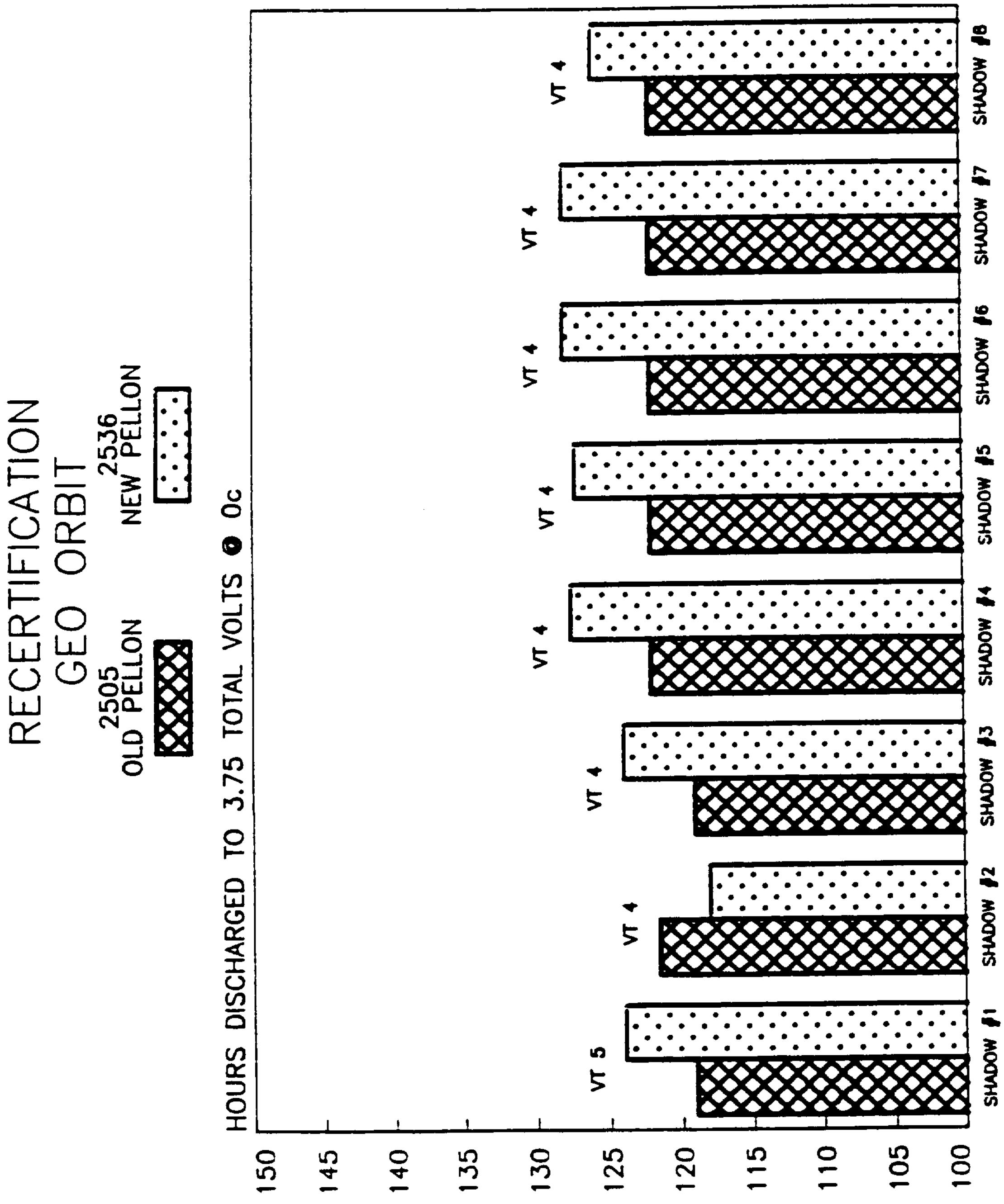


FIGURE 22. FRANCIS

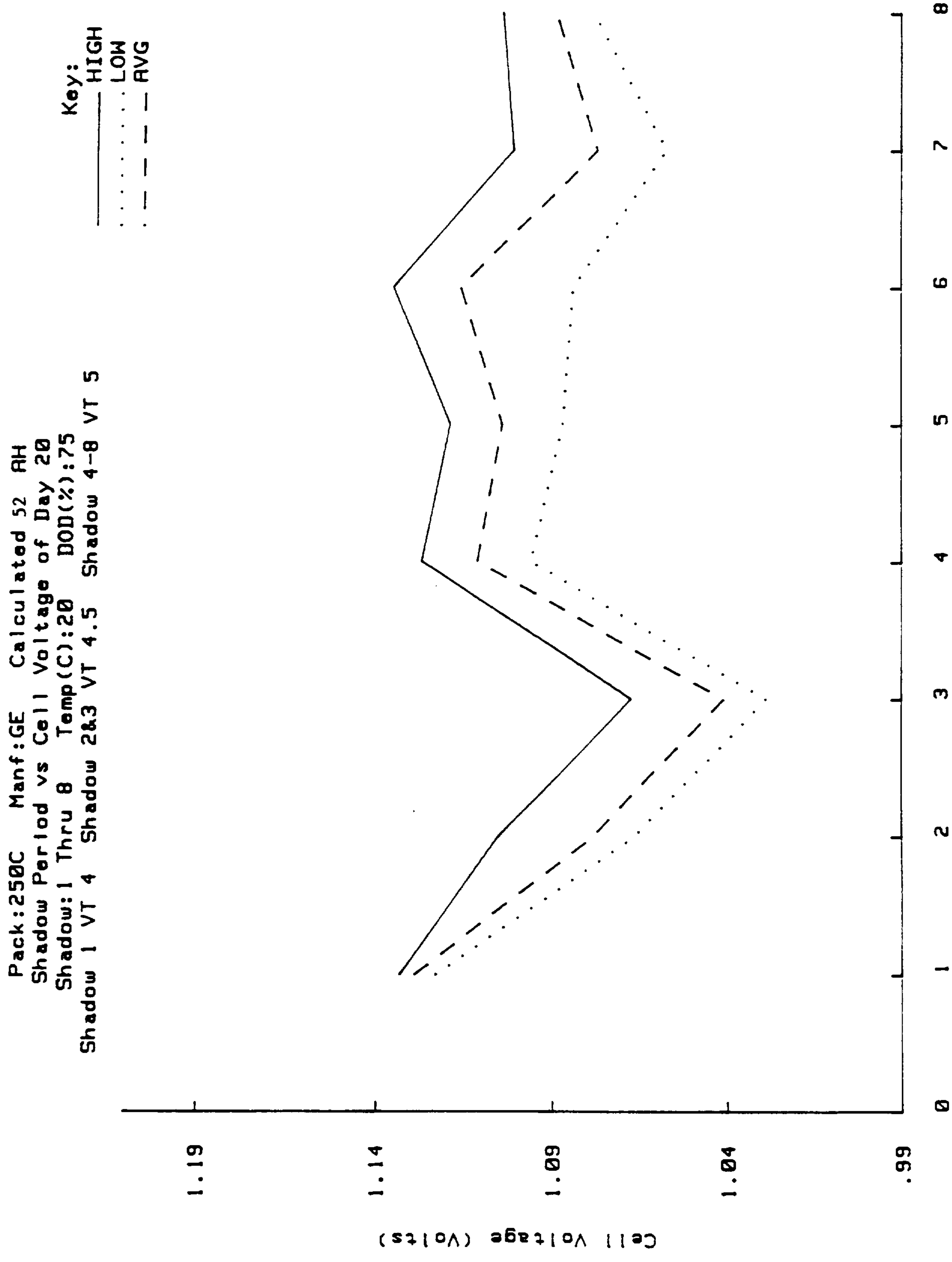


FIGURE 23. FRANCIS

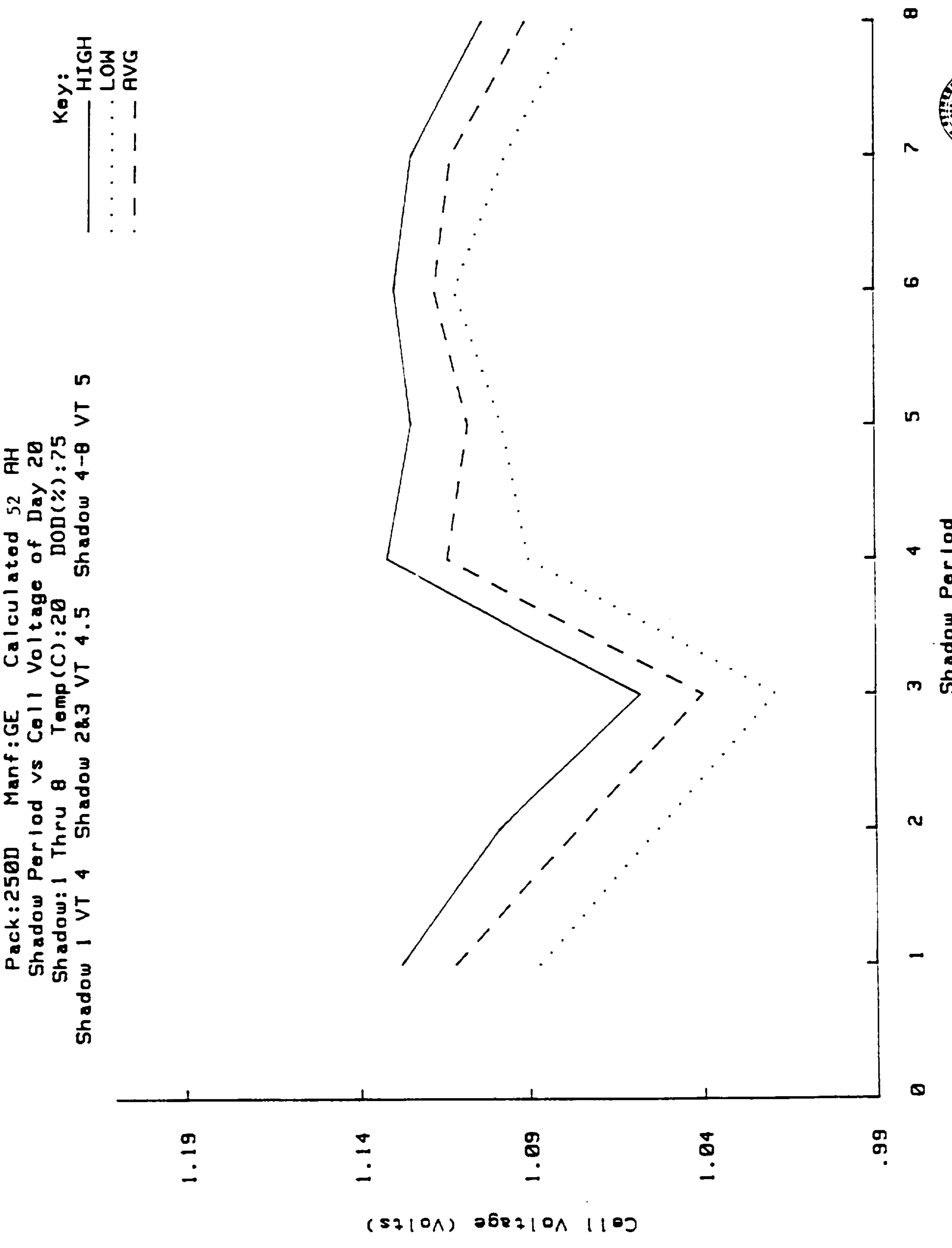


FIGURE 24. FRANCIS

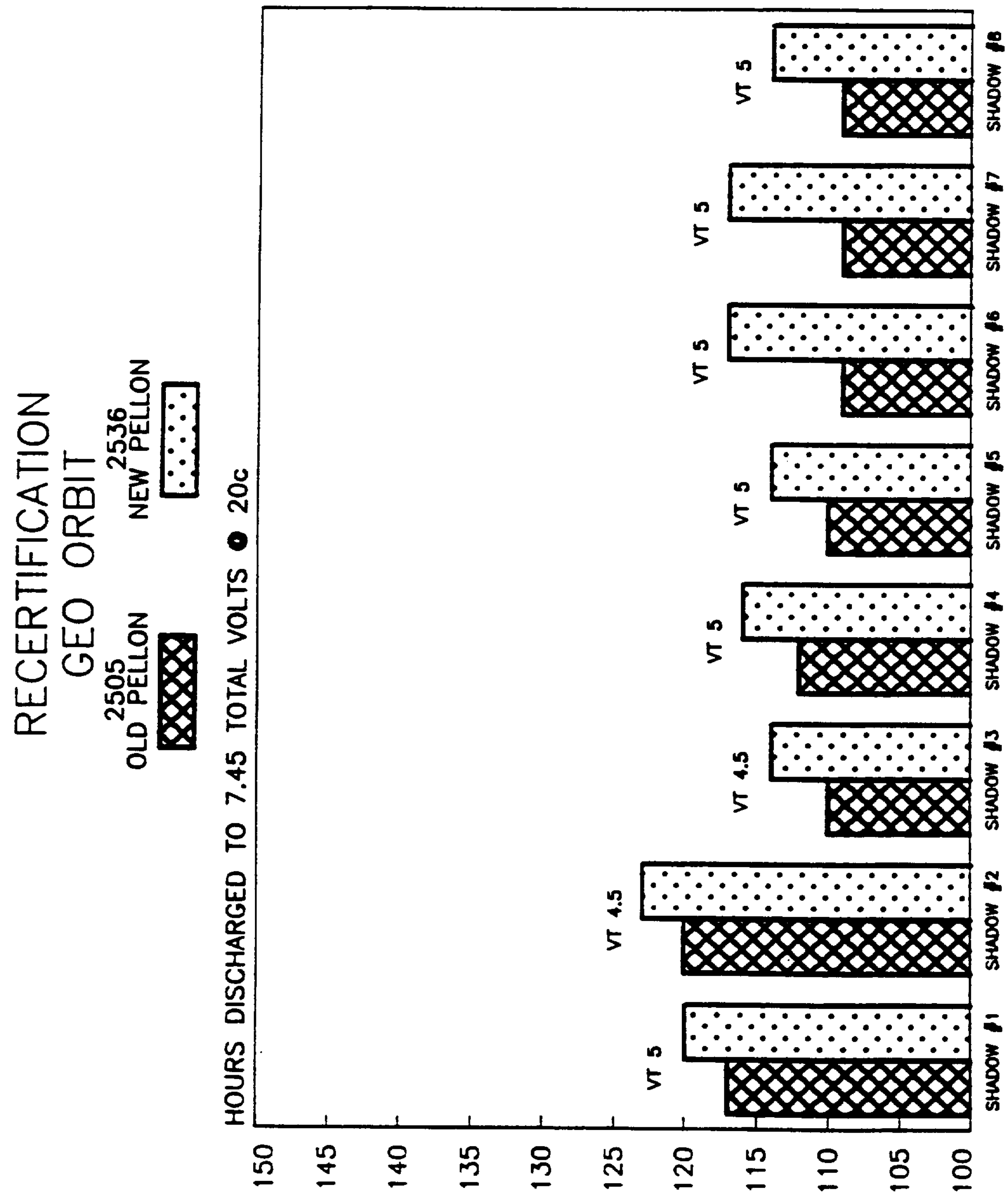


FIGURE 25. FRANCIS

- SUMMARY, ANALYSIS AND PLANS
  - CONCLUDE 35AH CELL DISPOSITION
  - CONTINUE CYCLING REMAINING LEO AND GEO PACKS TO FAILURE
  - ARRANGE DPA'S AND DETAILED ANALYSIS OF FAILED CELLS
  - IN SOME FLIGHT PROGRAMS CELLS MAY PERFORM ACCEPTABLY
  - EACH CASE MUST BE EVALUATED ACCORDING TO APPLICATION
  - CONSIDER ADDITIONAL TESTING
  - ANNUAL REPORT AVAILABLE END OF 1987 CALENDAR YEAR

FIGURE 26. FRANCIS

"UPDATE ON THE QUALIFICATION TESTING OF GE 50 NiCd CELLS WITH 2536 SEPARATOR AND PASSIVATED POSITIVE PLATES"

GEORGE MORROW

George Morrow (NASA/GSFC) gave an "Update on the Qualification Testing of GE 50Ah NiCd Cells with 2536 Separator and Both Passivated and Unpassivated Positive Plates."

Dave Baer started the life-cycling effort before he left the GSFC in 84. Morrow picked up on Baer's work and included some new analyses. The work calls for comparing new and old separator material, 2505ML and 2536, and also testing the positive plate processing that Gates had implemented. The cells being reported have been on test since 1985. Pack 150A, (Morrow [Figure 3]), was the NASA standard with the old separator and unpassivated positive plate. Temperatures were found to be going up to 24 to 25 degrees C. Now temperatures are kept around 15 degrees C, and there haven't been as many problems. Morrow [Figure 3] shows that there was an imbalance created in the cells; four of the cells are still cycling. Pack 150B has the new separator material and does not exhibit the problem as severely. Pack 150C had a problem after cycle 5830. Since 150C did not work well with VT-controlled charge, constant current control was tried. (Morrow [Figure 4])

After 1500 cycles at 0 degrees C, Pack 150G started to "act up" and could not be cured. When the temperature was raised from 0 to 15 degrees C it behaved well (Morrow [Figure 5]).

Reconditioning helped as a corrective action but when the reconditioned cell was put back in the pack other cells failed (Morrow [Figure 6]). The tested cells have been sent back to the vendor for analysis. The old and the new packs differ only in their negative electrodes. Everything else has been varied but to no avail.

Q. Webb (Martin): When do you expect the analysis to be done?

A. Hope to have it by the end of the year.

Q. Webb (Martin): Do we have to wait until the next Workshop?

A. There should be some results coming from NWSC Crane--maybe by the end of the year.

Q. Koehler (FORD): When the cell voltages started to disperse, apparently the cell that was low in discharge was also low on charge?

A. That's true

Q. Thierfelder (GE): Are these new NASA standard cells in 50 amp-hour packs?

A. These were in the NASA standard 50Ah cells as flown on Landsat-4 and 5 and ERBS in the early 1980's.

Q. Methlie (U.S. Govt): Do you have the temperatures for the cell that was low in EOCV and EODV? Did you check for shorts?

A. The temperature of the failed cell was not monitored. The thermistor was on the other cell. We didn't have any indication of shorts - a scope wouldn't have shown them.

Comment: Lim (Hughes) When we changed separators in our test cells we found that the cell characteristics depend strongly on the separator type.

Q. Methlie (U.S. Gov't): Regarding intermittent shorts, depending on whose model you use, you would normally expect 20,000 - 30,000 cycles before problems arise. In your case it happened at about 1/3 of that. When you short them out it may bring them back for a while.

A. Reconditioning helped performance for 500-700 cycles then it returned to the same state as before.

Q. Maurer (Bell Labs): The cells that were low in voltage were also low in capacity. Was that what you meant to say?

A. Yes. (The cells that were low in voltage were also low in capacity.)

Q. Maurer (Bell Labs): Did the charge-retention test show the dispersion?

A. The charge retention test, performed after reconditioning did not show the dispersion. The cells performed nominally.

The Wednesday session of the Battery Workshop adjourned.

QUALIFICATION TESTING OF GENERAL ELECTRIC 50 AMPERE-HOUR NICKEL-CADMIUM CELLS WITH PELLON 2536 SEPARATOR AND PASSIVATED POSIVATED POSITIVE PLATES

PRESENTED AT:

THE 1987 NASA/GODDARD SPACE FLIGHT CENTER BATTERY WORKSHOP

HELD AT:
NASA/GODDARD SPACE FLIGHT CENTER

NOVEMBER 4-5, 1987

LIFE CYCLING TEST MATRIX

ORBIT	DOD	TEMP (^oC)	NASA STD. CELLS	OLD POS. NEW SEP.	NEW POS. OLD SEP.	NEW POS. NEW SEP.
LEO	40	20	PACK 150A 42B050AB20 S/N 2-7	PACK 150B 42B050AB25 S/N 2-7	PACK 150C 42B060AB26 S/N 2-8	PACK 150D 42B060AB27 S/N 3-6,11,12
GEO	80	20		PACK 150H 42B050AB25 S/N 1,8-12		PACK 150I 42B050AB27 S/N 1,7-10
LEO	40	0				PACK 150G 42B050AB27 S/N 2,13-16

FIGURE 2. MORROW

TEST STATUS AND OBSERVATIONS

PACK 150A

9980	• CELLS 1 & 2 LOW VOLTAGE ON CHARGE FORCED 3, 4, & 5 OVER 1.5 VOLTS • CAPACITY REVEALED LOSS OF 16 AH AND 11 AH RESPECTIVELY • C/20 RECHARGE AT R.A. CAUSED CELL 1 OVERPRESSURE AT 90 PSI AND OVERVOLTAGE AT 1.526 VOLTS
9981	• CELLS RETURNED TO CYCLING
10298	• CYCLE PLOT
10627	• IMBALANCE IN PACK BETWEEN CELLS 1 & 2 AND 3, 4, & 5
10629	• CAPACITY REVEALED LOSS OF BETWEEN 11 AND 17 AH • CELL REMOVED FOR ANALYSIS

150 B

PROBLEM NOT AS SEVERE

CELL REMOVED FOR ANALYSIS

150 C

CONSTANT PROBLEM WITH PACK IMBALANCE AFTER CYCLE 5830

7161	• CELL 4 REMOVED AND CYCLED SEPARATELY • THERMAL RUNAWAY AT CYCLE 216 • CELL 4 REMOVED TO BE ANALYZED
7588	• CELL 5 EXHIBITED HIGH VOLTAGE ON CHARGE 1.52 VOLTS
7868	• REGIME CHANGED TO CONSTANT CURRENT CHARGE 40A TO 1.05 RETURN 6A FOR REMAINDER OF CHARGE PERIOD • PACK IMBALANCE CONTINUED BUT NO EXACERBATED BY VOLT LIMIT

150 D

6563	• CELL 2 LOW VOLTAGE ON CHARGE FORCING OTHERS HIGH • CELL 2 REMOVED FROM CIRCUIT, CHARGED, AND RETURNED
8768	• CELL 2 LOW ON CHARGE • REMOVED CELL 2 FOR ANALYSIS

FIGURE 4. MORROW

150 G

AFTER INITIAL IMBALANCE PROBLEMS AT 0°C (2864) PACK CYCLED WELL AT 15°C

8047 • CELL 2 REMOVED FOR ANALYSIS

150 H & I

GEO PERFORMANCE VERY GOOD UNTIL ECLIPSE SEASON 4

IN SEASON 4 PACKS EXHIBITED SEVERE VOLTAGE DROPOFF AT HIGHEST DOD'S

FIGURE 5. MORROW

CORRECTIVE ACTION RESULTS

PACK RECONDITIONING	CONDITION CORRECTED FOR 500 TO 1000 CYCLES
CELL RECONDITIONING	CONDITION CORRECTED WITHIN 500 CYCLES CELLS NOT CONDITIONED ARE LOW ON CHARGE
CELL RECHARGE CYCLES	CONDITION CORRECTED FOR 100 TO 500 AND THEN SAME CELL OUT OF BALANCE

FIGURE 6. MORROW

OBSERVATIONS

- CHARGE RETENTION, CHARGE EFFICIENCY, VOLTAGE RECOVERY TESTS REVEAL NO ANOMALIES
- PROBLEM EXHIBITED BOTH IN PACKS WITH NEW SEPARATOR AND OLD AND WITH POSITIVE PLATE PASSIVATION AND WITHOUT
- SIMILARITY IN PACK DESIGN RESTS WITH NEGATIVE ELECTRODES

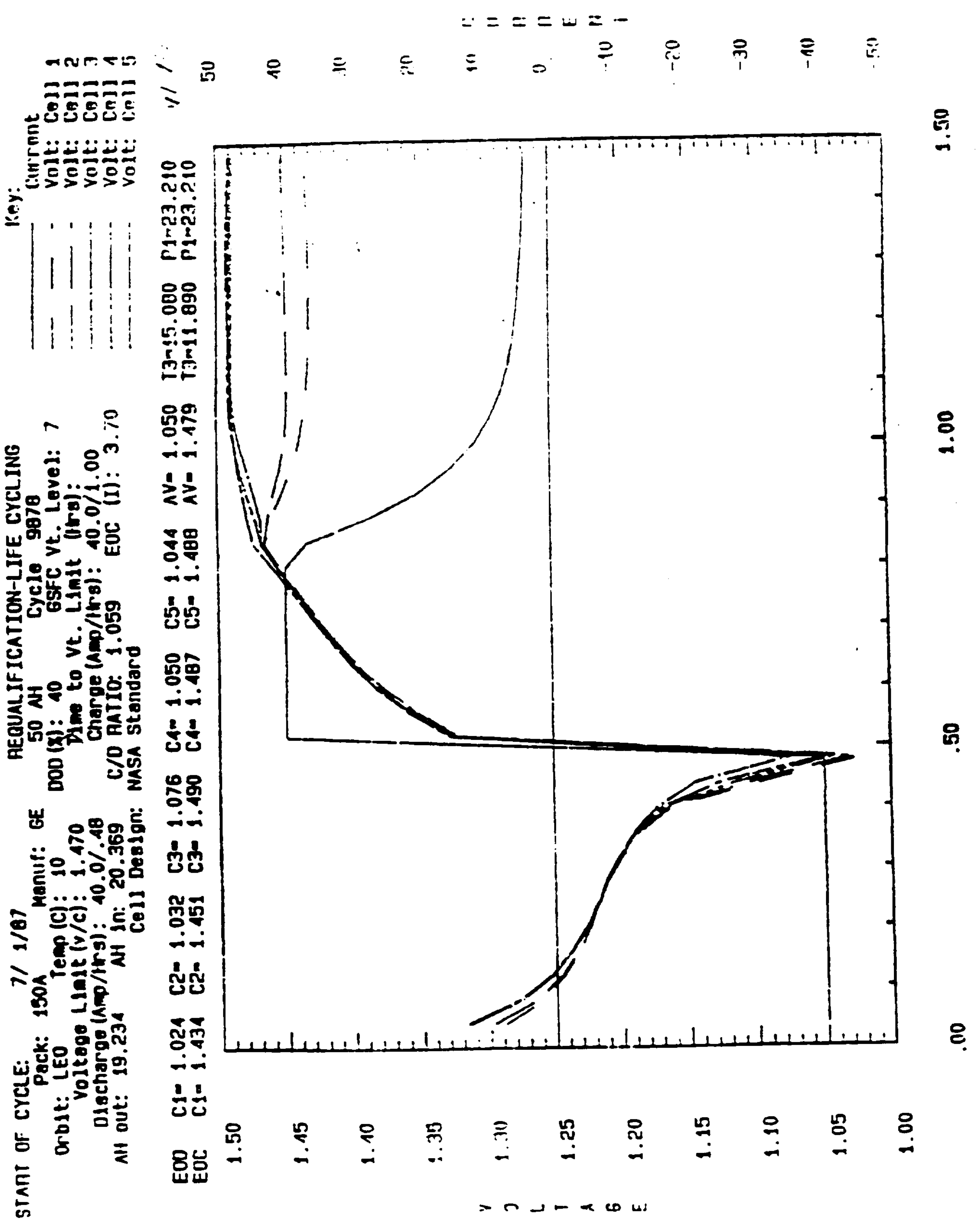


FIGURE 8. MORROW

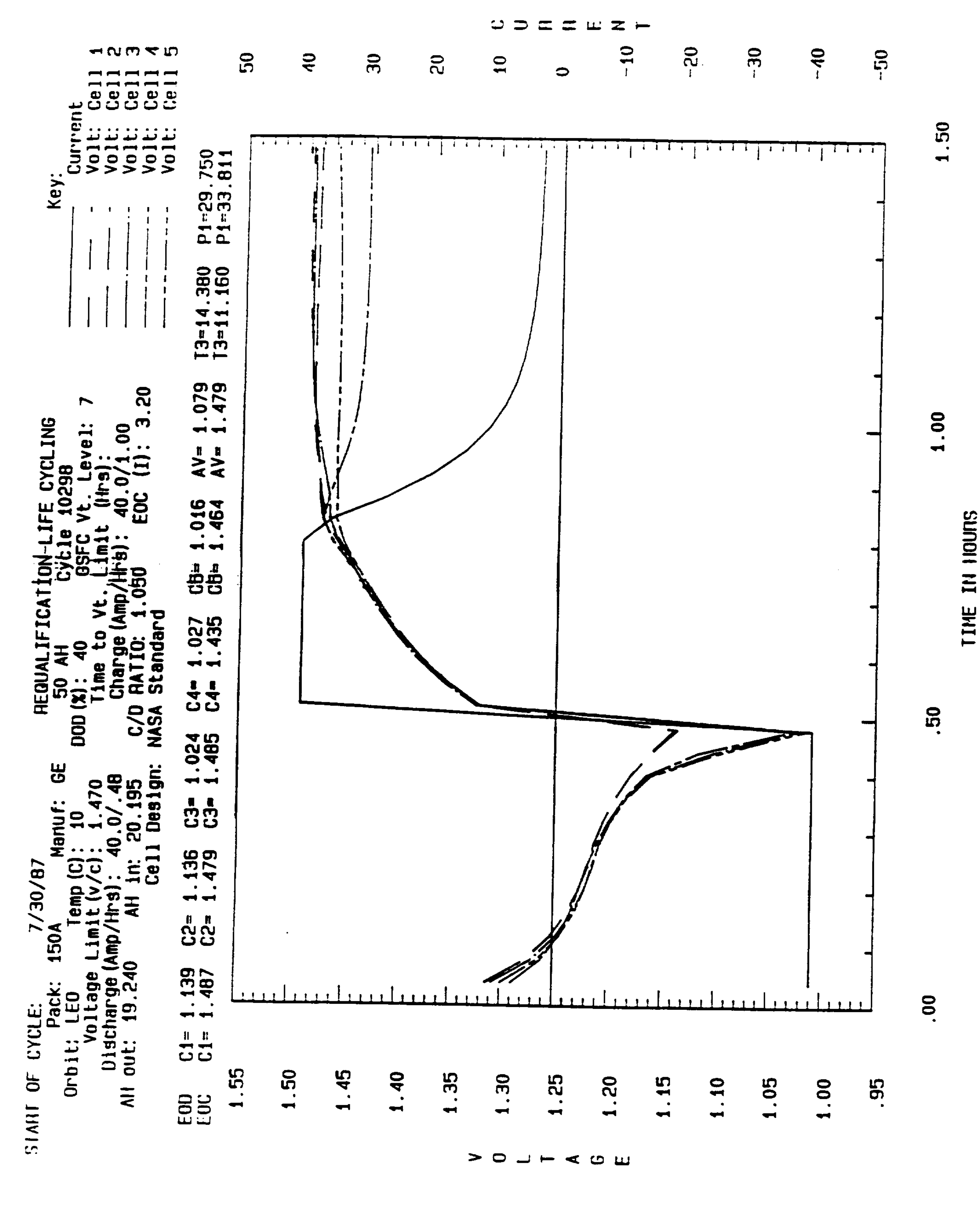


FIGURE 9. MORROW

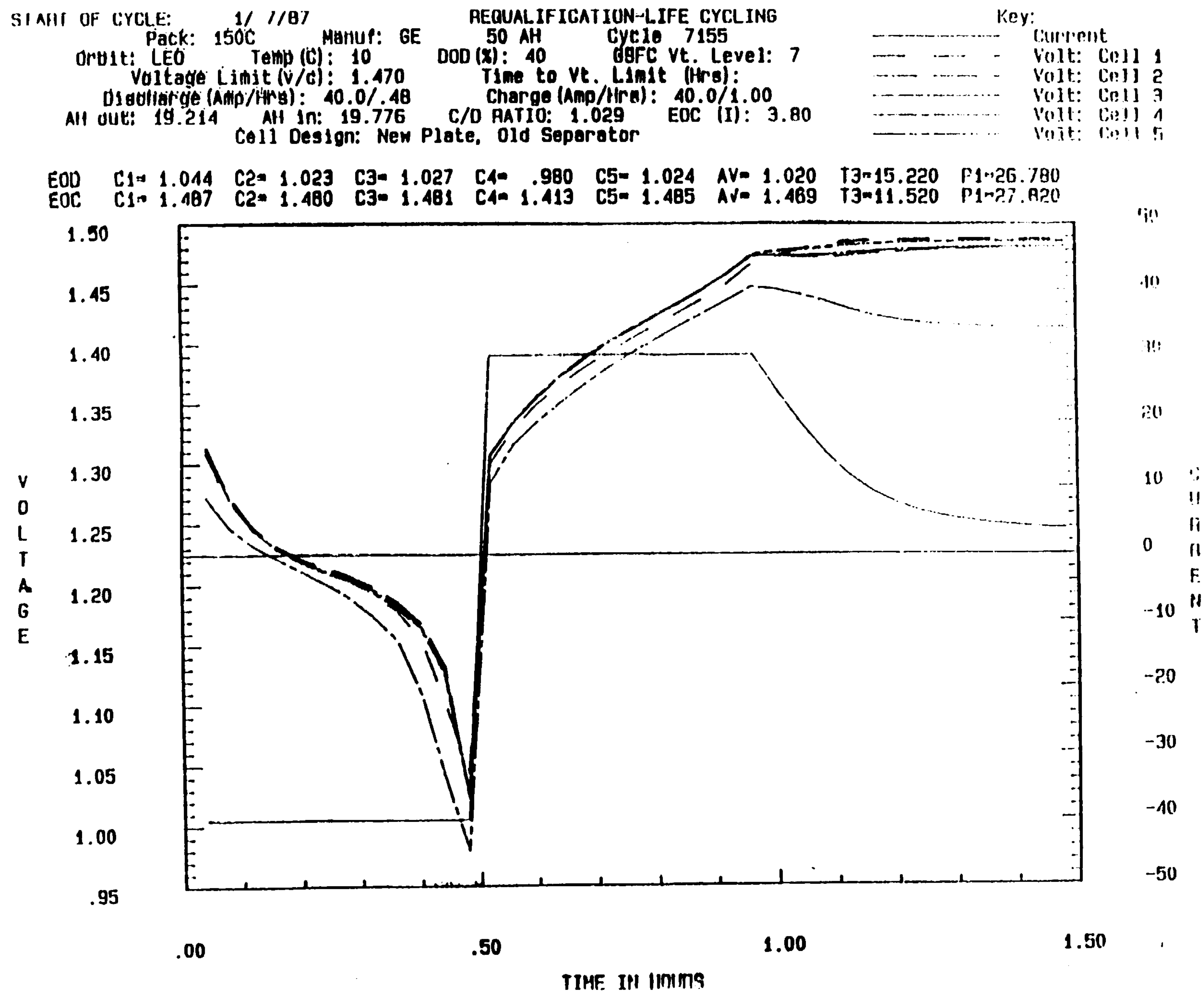


FIGURE 10. MORROW

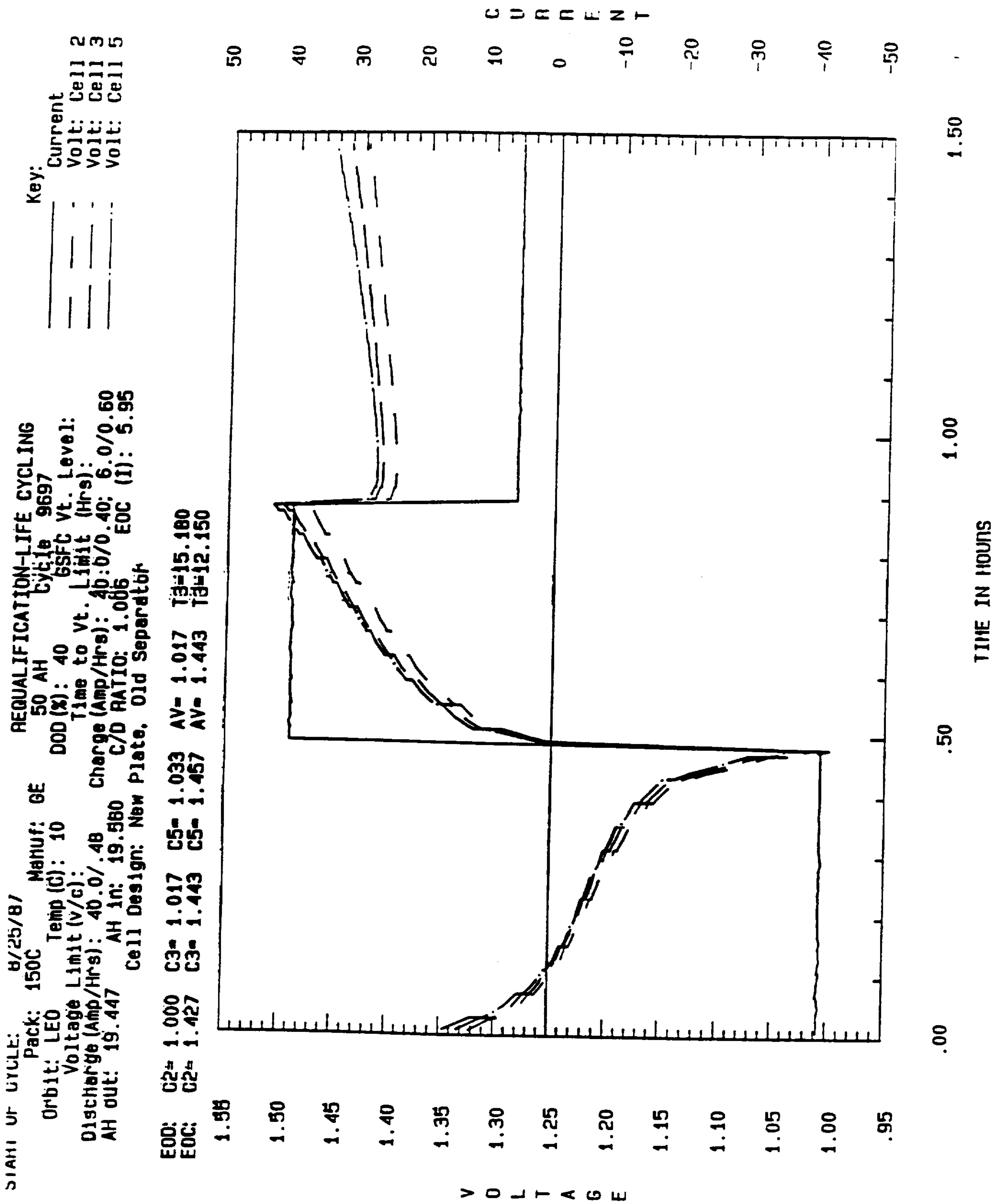


FIGURE 11. MORROW

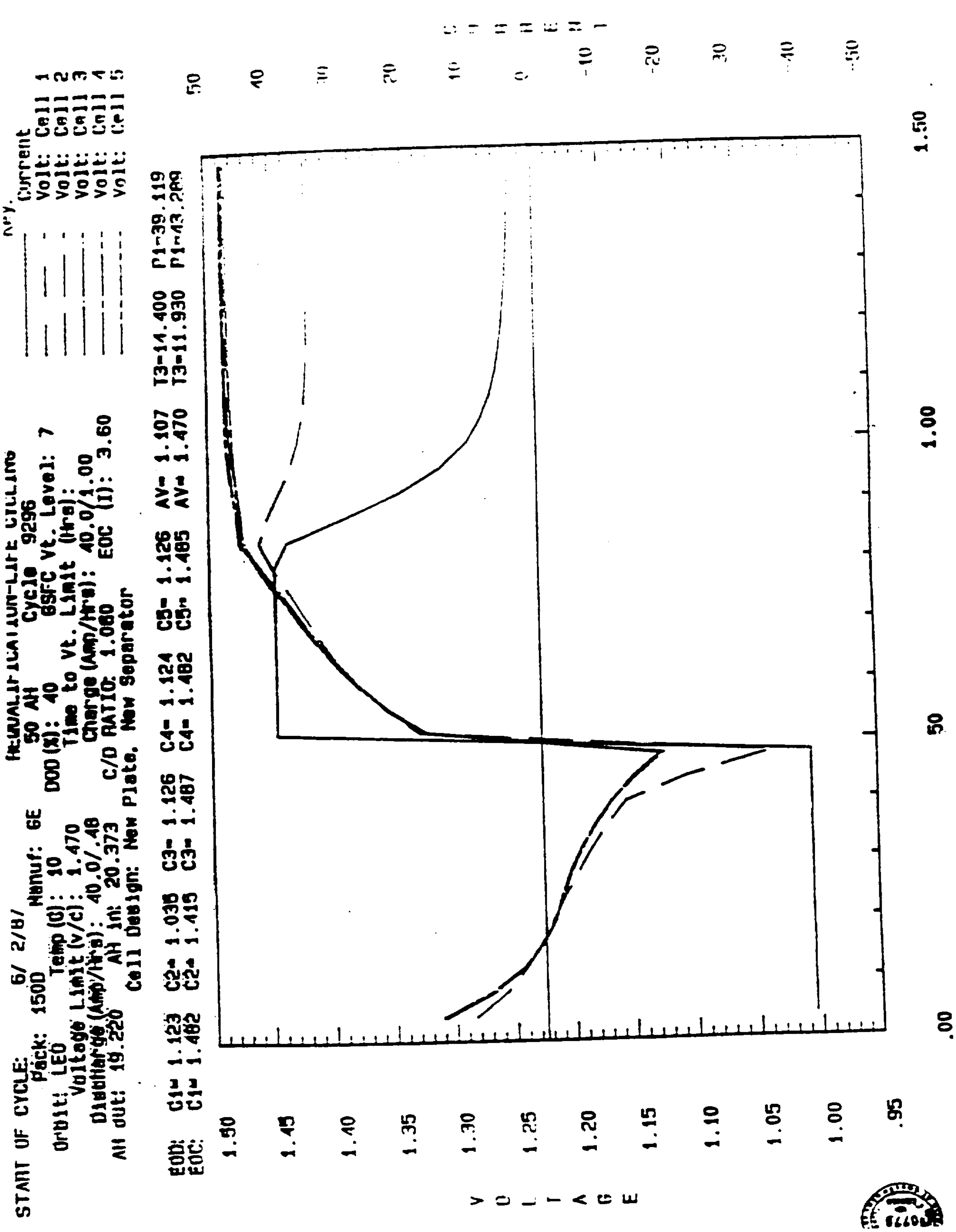


FIGURE 12. MORROW

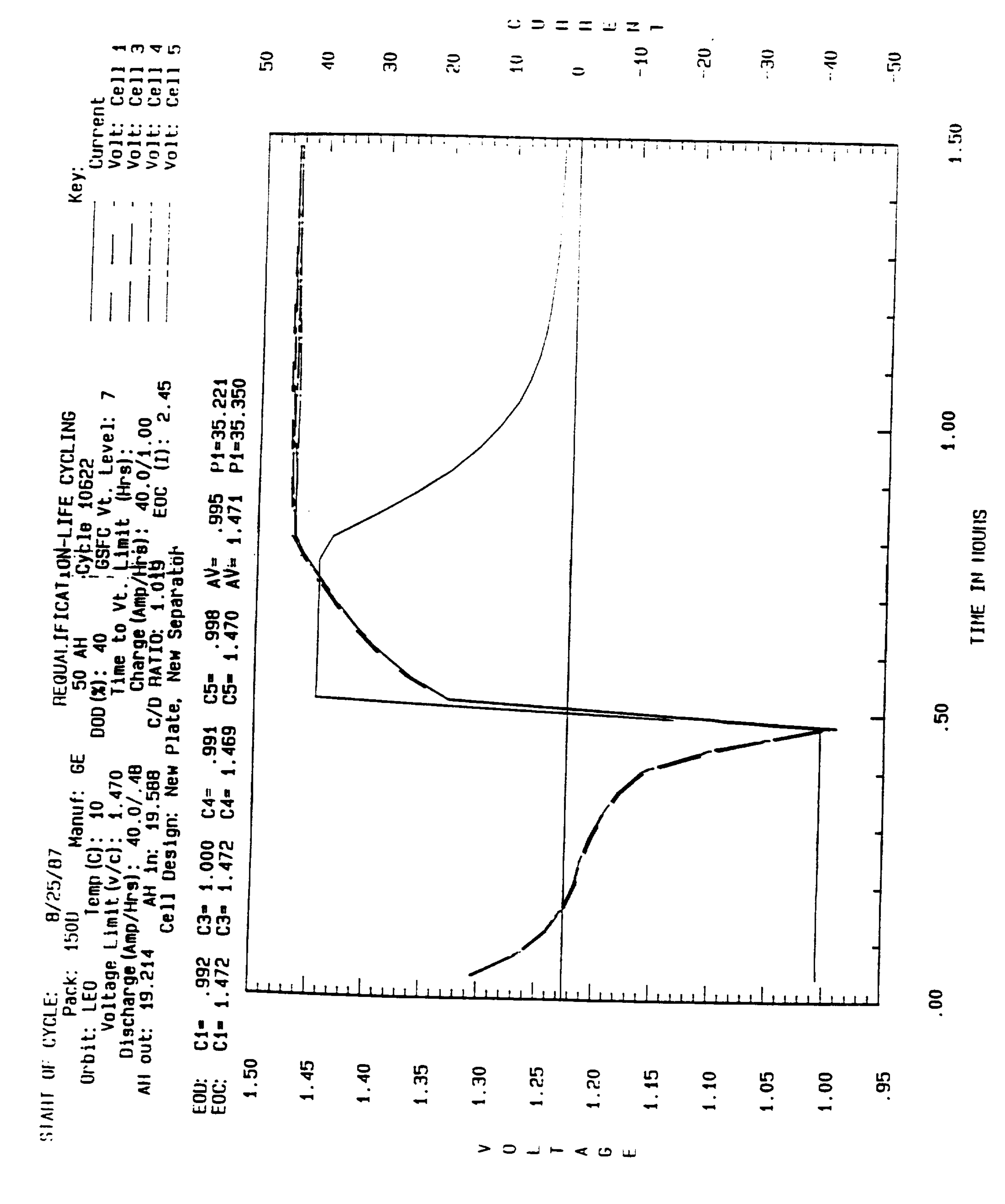


FIGURE 13. MORROW

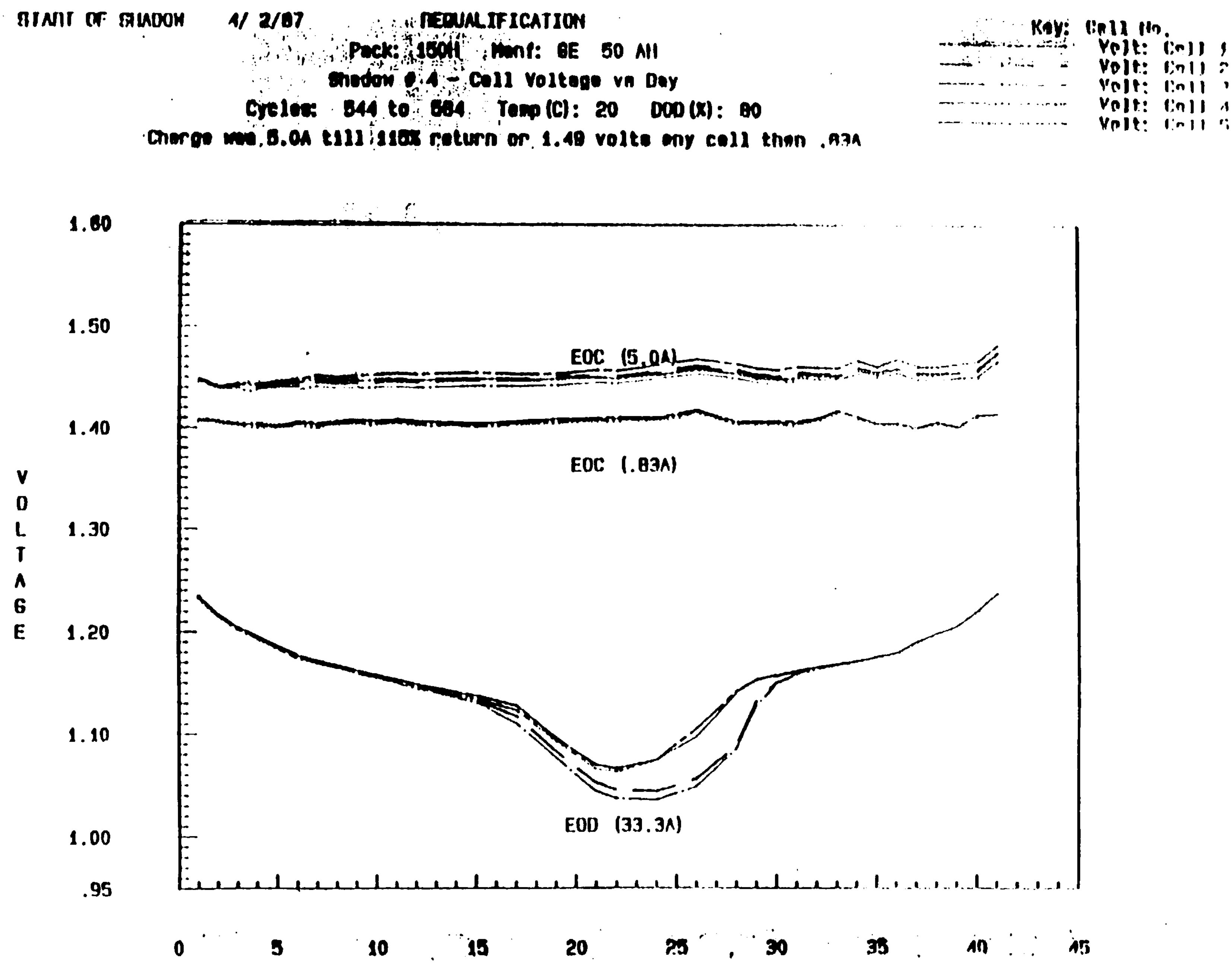


FIGURE 14. MORROW

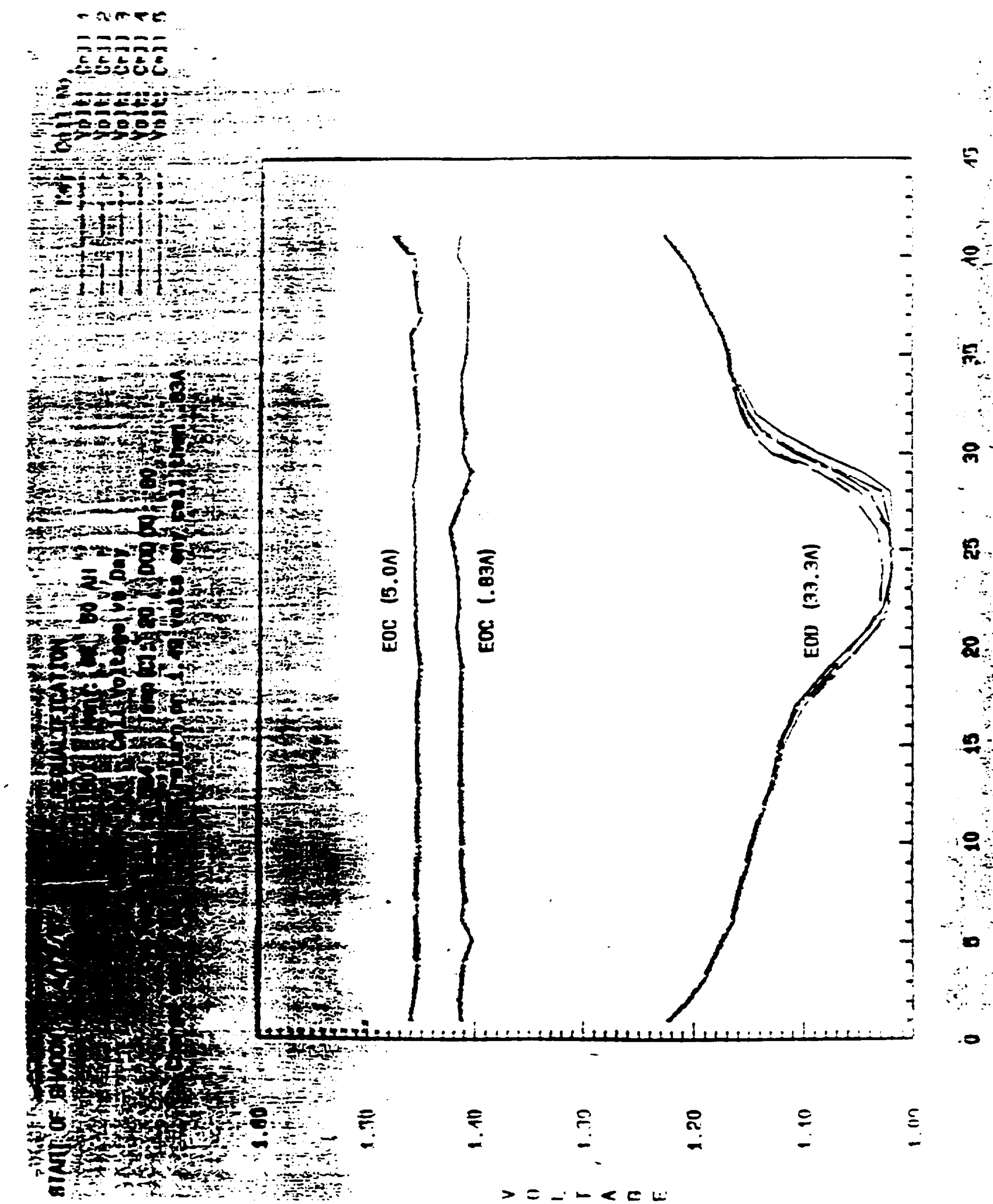


FIGURE 15. MORROW

ORIGINAL PAGE IS
OF POOR QUALITY

"NiCD CELL COMMON DATA POOL:PROGRESS AND STATUS REVIEW"

WARREN HWANG

Following the afternoon coffee break the first speaker was Warren Hwang (Aerospace Corp.) on "NiCd Cell Common Data Pool: Progress and Status Review."

Hwang said that there is a need to establish procedures for exchange of data across Air Force program and contractor lines (Hwang [Figure 2]). The electrical tests at NWSC (Crane) give commonality to the tests. Data on cell components are given just for the type of cell and not for the specific program. The data presented at the workshop for the cell acceptance tests are for 35 amp-hour tests.

There is a question about combining data from different lots (Hwang [Figure 9]). The lot-to-lot variation shows different populations although they may appear the same in orbit. It is desirable that data from acceptance tests come from tests that are done in the same manner.

To use data in the common data pool, they would like to combine different cell sizes, types, etc. When combinations of different kinds of cells are evaluated, different variations due to kind rather than lot-to-lot, become significant.

The criterion for evaluation is given as T, where T is a measure of the variation in kind (Hwang [Figure 11]). If means are far apart, T will be large. L is the measure of the lot-to-lot variation. The use of R as a discriminator is not hard and fast but it is helpful.

The results of evaluations, (Hwang [Figure 12]), bring out these points:

--The manufacturing process change in 1980 caused a difference in voltage output; therefore pre-and post-1980 data cannot be combined.

--The question remains: can information from different programs be combined? This program indicates good results for combining information from different programs.

--The sample size for 15 amp-hours is very small, and therefore not much can be concluded. The choice of R=5 as a criterion is not settled.

The results shown in the chart "Standard Electrical Characterization" at NWSC, (Hwang [Figure 14]), are from Crane tests of five sample cells. There were about 500 orbital cycles.

Q. Timmerman (JPL): Will you release other material on your programs?

A. The program format is rigid right now, but you could combine data from the individual lots.

NICKEL CADMIUM CELL COMMON DATA POOL: PROGRESS AND STATUS REVIEW

Goddard Space Flight Center

Battery Workshop

4 November 1987

W. Hwang, S. Donley, G. Collins, J. Matsumoto

The Aerospace Corporation

Los Angeles, CA 90009

FIGURE 1. HWANG

BACKGROUND

* Wide Range in Lot-to-lot Characteristics for NiCd Cells Manufactured in Past Several Years

* Atypical Characteristics in Some Lots Have Led to Rejection for Flight
  * Minority of lots show atypical characteristics
  * Several AF programs affected

* Limited Database
  * Limited data available for individual program or contractor
  * No standard testing for AF programs
  * Current data hard to obtain

* Need to Establish Procedure for Exchange of Data Across AF Program and Contractor Lines

Figure 2. Hwang

SCOPE OF PROGRAM

- DATA FROM FUTURE LOTS
  - FLIGHT CELLS
    - SELECTED RESULTS FROM COMPONENT ANALYSIS
    - SELECTED RESULTS FROM ACCEPTANCE TEST
  - FIVE TEST CELLS FROM EACH LOT
    - ACCEPTANCE TEST RESULTS
    - ELECTRICAL TEST AT NWSC (CRANE)
      - NO PASS/FAIL CRITERIA
    - SUBSEQUENT DPA OF FOUR CELLS AT MANUFACTURER
      - NO PASS/FAIL CRITERIA

- DATA FROM PRESENT LOTS
  - FLIGHT CELLS: SAME AS ABOVE
  - LOT SCREEN TESTS
    - SELECTED RESULTS OF ELECTRICAL PERFORMANCE
    - RESULTS OF DPA

FIGURE 3. HWANG

PROGRESS OF PROGRAM

* SUGGESTIONS FROM PROGRAMS AND CONTRACTORS INCORPORATED

* CAPABILITY TO COMPILE AND REPORT DATA IN PLACE
  * PROCEDURES AND SOFTWARE IN PLACE
  * TWELVE INTERNAL MONTHLY REPORTS
    * DATA FROM PRESENT LOTS
    * PENDING FORMAL APPROVALS FOR EXTERNAL DISTRIBUTION

* CAPABILITY FOR ELECTRICAL TESTING IN PLACE
  * PROCEDURES AND TEST STATION ESTABLISHED
  * TESTS FOR FOUR LOTS COMPLETED

FIGURE 4. HWANG

DATA ON CELL COMPONENTS

CATALOG AND LOT NUMBER: 35ABAA-05

CD ELECTRODE:

TREATMENT: AG

SINTER DATE: 02/26/85

COATED WEIGHT: 10.33 GM/DM^2

LOADING LEVEL: 15.30 GM/DM^2

NI ELECTRODE:

SINTER DATE: 02/21/85

COATED WEIGHT: 10.39 GM/DM^2

LOADING LEVEL: 13.20 GM/DM^2

ELECTROLYTE, KOH:

FILL DATE: 12/09/85

AMOUNT: 84.00 CC

CONCENTRATION: 31.00%

SEPARATOR TYPE: 2505

DATA FROM CELL ACCEPTANCE TESTS

CAPACITY TEST AT 25°C

NO. OF CELLS: 118

CAPACITY (AMPERE-HOURS) TO 1.0 V DISCHARGE VOLTAGE LIMIT

MAX VALUE: 39.02

MIN VALUE: 35.88

MEAN: 37.04

STD. DEV.: 0.443

SKEWNESS: 0.883

KURTOSIS: 3.86

PEAK VOLTAGE (VOLTS)

MAX VALUE: 1.465

MIN VALUE: 1.450

MEAN: 1.457

STD. DEV.: 0.003

SKEWNESS: 0.151

KURTOSIS: -0.270

SIMILAR DATA FOR OVERCHARGE TEST AT OR NEAR 0°C

FIGURE 6 HWANG

DATA FROM CELL ACCEPTANCE TESTS

CAPACITY TEST AT 25°C (CONT.)

END-OF-CHARGE VOLTAGE (VOLTS)

MAX VALUE: 1.463
MIN VALUE: 1.442
MEAN: 1.454
STD. DEV.: 0.004
SKEWNESS: 0.085
KURTOSIS: -0.406

PEAK PRESSURE (PSIG)

MAX VALUE: 15
MIN VALUE: 0
MEAN: 8.0
STD. DEV.: 2.4
SKEWNESS: 0.41
KURTOSIS: 0.78

SIMILAR DATA FOR OVERCHARGE TEST AT 0°C

FIGURE 7. HWANG

DATA FROM DPA AT MANUFACTURER

CELL S/N: 037

TYPE OF TESTING: ACCEPTANCE TEST

NICKEL ELECTRODE:

CHEMICAL CAPACITY: 49.40 AH

ELECTROCHEMICAL CAPACITY: 43.10 AH

CADMIUM ELECTRODE:

CHEMICAL CAPACITY: 79.40 AH

ELECTROCHEMICAL CAPACITY: 73.50 AH

CADMIUM PRECHARGE: 11.50 AH

CADMIUM OVERCHARGE: 18.90 AH

FIGURE 8. HWANG

COMBINING DATA FROM DIFFERENT LOTS

* DATA FROM ACCEPTANCE TESTS OF FLIGHT CELLS
  * TEST CONDITIONS ARE PROGRAM AND CONTRACTOR SPECIFIC
  * USE DATA THAT CORRESPOND TO STANDARD CONDITIONS OF TEMPERATURE, NORMALIZED CHARGE RATE, NORMALIZED DISCHARGE RATE, AND END OF CAPACITY DISCHARGE VOLTAGE
  * NORMALIZATION OF CAPACITY BY NICKEL ELECTRODE GEOMETRIC AREA

* STANDARDIZED TESTS OF FIVE TEST CELLS PER LOT
  * STANDARD TEST CONDITIONS
  * NORMALIZATION OF CAPACITY, CHARGE RATE, AND DISCHARGE RATE BY NICKEL ELECTRODE AREA

* NEED TO DETERMINE IF DATA SHOULD BE COMBINED
  * SAME CELL SIZE AND CELL TYPE
  * DIFFERENT CELL SIZE
  * DIFFERENT CELL TYPE
  * DIFFERENT CELL SIZE AND CELL TYPE

FIGURE 9. HWANG

EVALUATION OF COMBINATION OF DIFFERENT KINDS OF CELLS

* COMPARE VARIATION IN DATA FOR CELLS OF DIFFERENT KIND (SIZE OR DESIGN) WITH LOT-TO-LOT VARIATIONS WITHIN ONE KIND OF CELL
  * EVEN TYPICAL LOT-TO-LOT VARIATIONS CAN RESULT IN DIFFERENT DISTRIBUTIONS OF DATA

* ONLY TWO KINDS OF CELLS EVALUATED AT ONE TIME

* NEED COMMON TESTS AND TEST CONDITIONS

* FOUR CASES EVALUATED
  * CAPACITY AT 0^{o} C
  * END OF CHARGE VOLTAGE AT 0^{o} C
  * CAPACITY AT 25^{o} C
  * END OF CHARGE VOLTAGE AT 25^{o} C

FIGURE 10. HWANG

CRITERION FOR EVALUATION

* VARIATION IN KIND: $T = \sum_{K} N_K (M_K - M_{MT})^2 / (2-1)$

  WHERE N_K = NO. CELLS OF A KIND, M_K = MEAN OF ALL CELLS OF A KIND

  AND M_{LK} = MEAN OF ALL CELLS OF BOTH KINDS

* VARIATION IN LOT: $L = \sum_{K} \sum_{L} N_L (M_L - M_K)^2 / (N-1)$

  WHERE N_L = NO. CELLS IN A LOT, M_L = MEAN OF ALL CELLS IN A LOT,

  AND N = TOTAL NO. OF LOTS

* NORMALIZED VARIATION: $R = T/L$

* IF $R < 5$ FOR ALL CASES, DATA OF BOTH KINDS CAN BE TABULATED TOGETHER

* IF $R > 5$ FOR ANY CASE , DATA CAN NOT BE TABULATED TOGETHER

FIGURE 11. HWANG

RESULTS OF EVALUATIONS

* PRE-1980 AND POST-1980 (AFTER MANUFACTURING PROCESS CHANGE IN NICKEL ELECTRODE) LOTS OF SAME SIZE, DESIGN, AND PROGRAM
  * R = 11.2 FOR 25^{0} C END OF DISCHARGE VOLTAGE
  * CAN NOT COMBINE DATA

* LOTS OF COMMON SIZE AND DESIGN BUT FROM DIFFERENT PROGRAMS (AND DIFFERENT CATALOG NUMBER)
  * R < 5 FOR ALL 4 TESTS
  * DATA CAN BE COMBINED

* LOTS OF DIFFERENT SIZE (15 & 35 AH) BUT SAME BASIC DESIGN
  * R > 5 FOR A TEST
  * TENTATIVELY CAN NOT COMBINE DATA
  * WILL REVIEW THIS PRELIMINARY RESULT AS DATABASE INCREASES

FIGURE 12. HWANG

SUMMARY OF DATA FROM CELL ACCEPTANCE TESTS

CAPACITY TEST AT 0^{o} C

AG NEGATIVES

2505 SEPARATOR

NO. OF CELLS: 354

CAPACITY TO 1.1 V DISCHARGE VOLTAGE LIMIT (AMPERE-HOURS):

MAX VALUE: 35.08

MIN VALUE: 32.20

MEAN: 33.91

STD. DEV.: 0.58

SKEWNESS: 0.27

KURTOSIS: -0.02

END-OF-CHARGE VOLTAGE (VOLTS)

MAX VALUE: 1.513

MIN VALUE: 1.443

MEAN: 1.481

STD. DEV.: 0.020

SKEWNESS: -0.068

KURTOSIS: -1.234

FIGURE 13. HWANG

STANDARD ELECTRICAL CHARACTERIZATION AT NWSC

AVERAGE FOR A 35 AH LOT

TEST	NO. CELL	CAPACITY	EOCV	PEAK VOLTAGE
PRECYCLE 25^{0} C	5	35.56 AH	1.432 V	-
PRECYCLE 0^{0} C	5	35.05 AH	1.512 V	1.536 V
PRECYCLE -10^{0} C	5	30.50 AH	1.529 V	1.541 V
POSTCYCLE 25^{0} C	3	36.06 AH	1.463 V	-
POSTCYCLE 0^{0} C	3	31.02 AH	1.514 V	1.544 V
POSTCYCLE -10^{0} C	3	25.78 AH	1.534 V	1.551 V
NO CYCLES 25^{0} C	2	35.31 AH	1.437 V	-
NO CYCLES 0^{0} C	2	35.88 AH	1.515 V	1.548 V
NO CYCLES -10^{0} C	2	30.96 AH	1.536 V	1.556 V

FIGURE 14. HWANG

PROGRAM STATUS

* CAPABILITIES IN PLACE
  * STANDARDIZED TESTING AT NWSC
  * COMPILATION OF DATA
  * EVALUATION OF DATA THAT CAN BE COMBINED
  * WRITING OF REPORTS
* EXTERNAL DISTRIBUTION OF REPORTS
* FORMAL ADOPTION IN NEW CONTRACTS

FIGURE 15. HWANG

"SEASONAL POWER VARIATIONS IN A LEO SATELLITE"

JIM MATSUMOTO

Jim Matsumoto's (Aerospace) presentation was on "Seasonal Power Variations in a LEO Satellite."

The original objective was to look at battery degradation on DMSP flight 7 (Matsumoto [Figure 2]). The DMSP has now been operating for 4 years despite the stated three-year mission life. Onboard tape recorders transmit data to the ground.

Seasonal variations occur with increased battery loads in Northern winters because most of the ground stations are in the Northern hemisphere.

The DMSP power subsystem operates at about 500 W (Matsumoto [Figure 3]). There are two 26.5Ah NiCd-17 cell batteries wired in parallel (Matsumoto [Figure 4]). The F7 battery data analysis, (Matsumoto [Figure 5]), included looking at the batteries in maximum stress conditions and looking at C/D ratios. F7 minimum battery voltages, (Matsumoto [Figure 6]), at EOD have a characteristic voltage recovery in summer months and a loss in winter months. F7 maximum pack temperatures at EOD (Matsumoto [Figure 7]), show a characteristic temperature rise in the winter months.

Toward the end of the test series the battery temperatures tend to stay high, near 12 degrees C. The State of Charge (SOC) near end of discharge is higher in the summer (Matsumoto [Figure 8]). Load sharing between the batteries seems to diverge over time.

A plot of the charge/discharge ratio, (Matsumoto [Figure 9]), shows the difference between the batteries. The plot of battery 2 discharge 1 vs battery 1 discharge 1, (Matsumoto [Figure 11]), shows load sharing divergence after one and one half years. A conclusion of the work is that there are seasonal effects on battery degradation (Matsumoto [Figures 12, 13, and 14]). It may be necessary to compensate for the seasonal variations. Knowledge of the likely variations may lead to more accurate predictions of battery performance.

Q. Dunnet (Intelsat): Describe the spacecraft itself.

A. Not familiar with it.

A. Gaston (RCA): The spacecraft is 3-axis stabilized; it has a single bus; it has four packs of batteries on opposite sides. Don't know the orbit inclination.

Q. Hutchins (FACC): What is the minimum battery voltage where the main bus loses regulation?

A. Gaston (RCA): At 12 volts the system cannot support the payload.

Q. Barnes (NRL): How do you optimize management? By not having batteries in parallel? By having individual battery charges?

A. The VT levels can be set separately.

Q. Timmerman (JPL): Is there an automatic recharging fraction and is it used?

A. Gaston (RCA): There are multiple VTs and a trickle option. However, the switch to trickle is not used.

Q. Prudhoe (Martin Marietta): How is the DOD calculated? Why isn't the battery fully charged?

A. The plots are from the onboard computer. EOD was plotted and not EOC.

SEASONAL LEO BATTERY OPERATION

GSFC Battery Workshop

4—5 November 1987

J.H. Matsumoto, W.C. Hwang and M.J. Milden
Aerospace Corporation
El Segundo, CA

FIGURE 1. MATSUMOTO

DMSP SATELLITE

- 450 nm — sun synchronous orbit
- Orbits vary from "terminator" through "noon"
  - 35 minute dark/65 minute light for noon orbit
- Three and one half year mission life
- Satellite transmissions to ground stations will increase battery usage during dark periods
- Seasonal variations in battery usage occur because most ground stations in North. Hemisphere

FIGURE 2. MATSUMOTO

DMSP POWER SUBSYSTEM

- o Boost regulator type system (28 +/– 0.56 V)
- o Operation: about 500 W
- o Power management software (on–board computer)
  - o Monitors (V,T,I), calculates (SOC)
  - o Backup (safety) control for high temp or low DoD
- o Four ground–commandable V–T curves for each battery to limit overcharge

FIGURE 3. MATSUMOTO

DMSP BATTERY CHARACTERISTICS

- o Two 26.5 Ah NiCd 17 cell batteries wired in parallel
  - o Two packs for each battery (8 cell & 9 cell)
- o Operating temperature: 6 to 12 deg.C
- o DoD: Design – 20%, Actual – 12% to 18%

FIGURE 4. MATSUMOTO

F7 BATTERY DATA ANALYSIS

- Minimum battery voltages (at EOD)
- Maximum pack temperatures (at EOD)
- Minimum state of charge for each battery
- C/D ratio
- EOC taper charge current
- Ratio of DoD near end of eclipse for Battery 2/Battery 1
- Ratio of Bat 2 Disch I/Bat 1 Disch I

FIGURE 5. MATSUMOTO

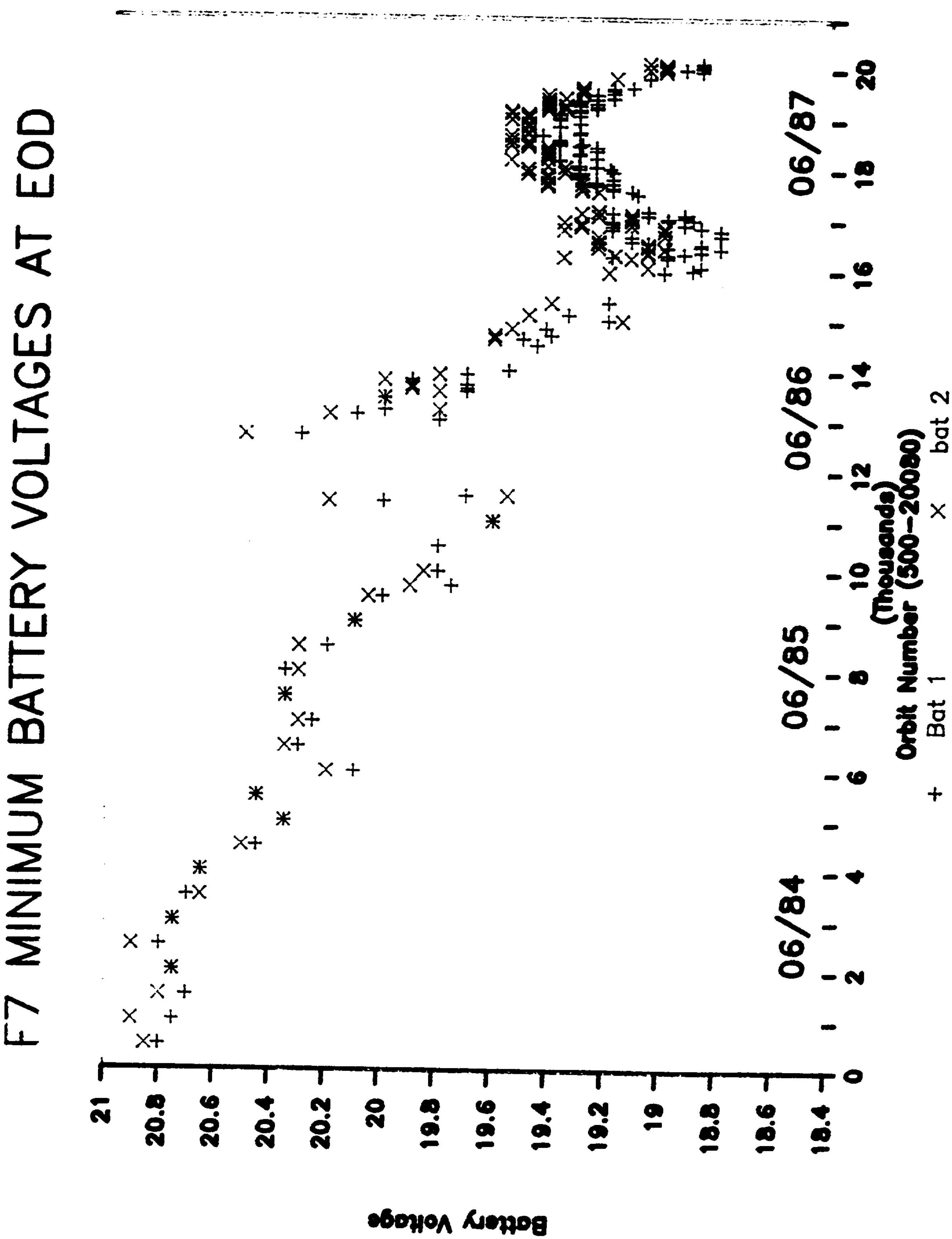
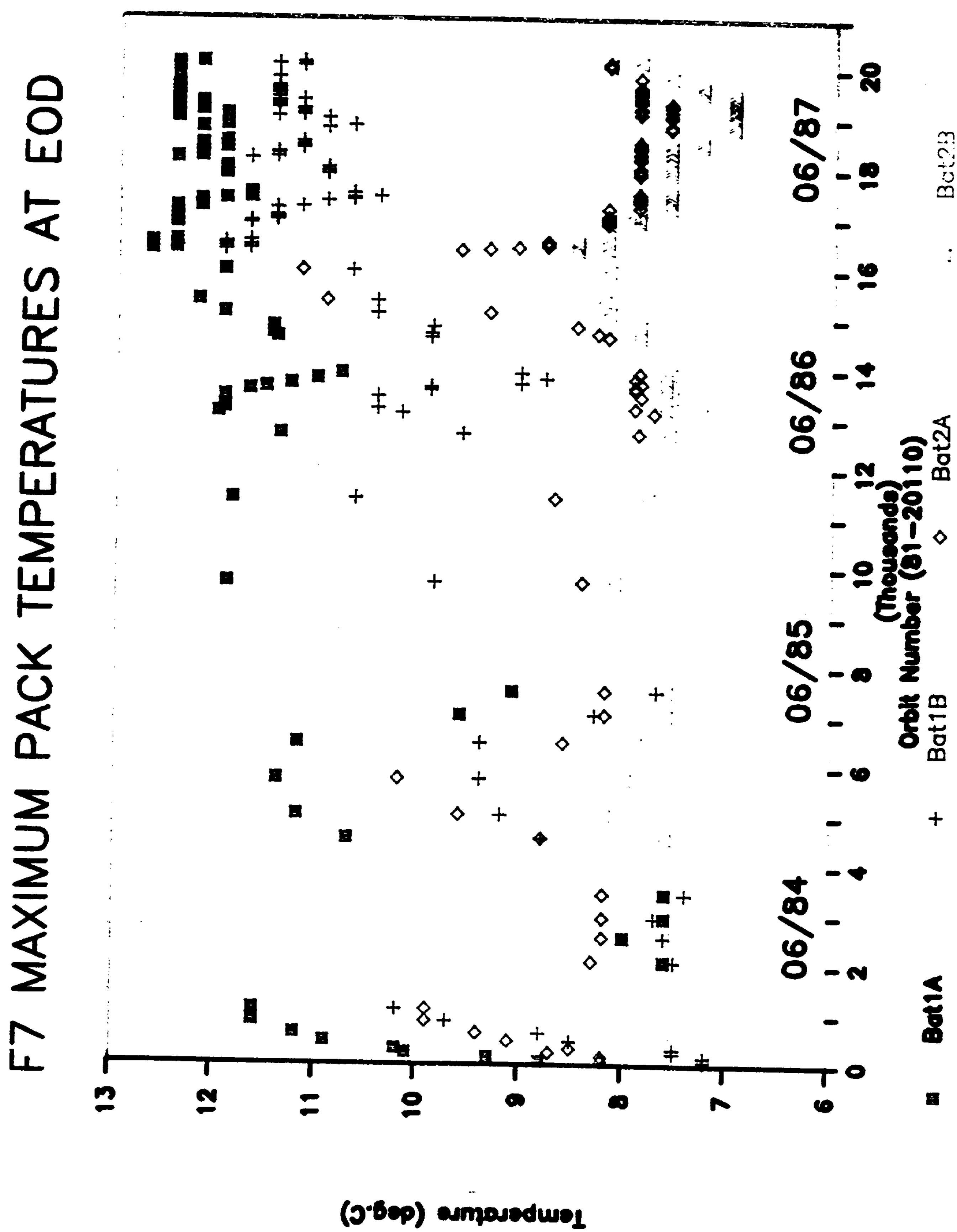


FIGURE 6. MATSUMOTO


F7 MAXIMUM PACK TEMPERATURES AT EOD
Temperature (deg.C)
13
12
11
10
9
8
7
6
0
2
4
6
8
10
12
14
16
18
20
Orbit Number (81–20110)
(Thousands)
06/84
06/85
06/86
06/87
Bat1A
Bat1B
Bat2A
Bat2B

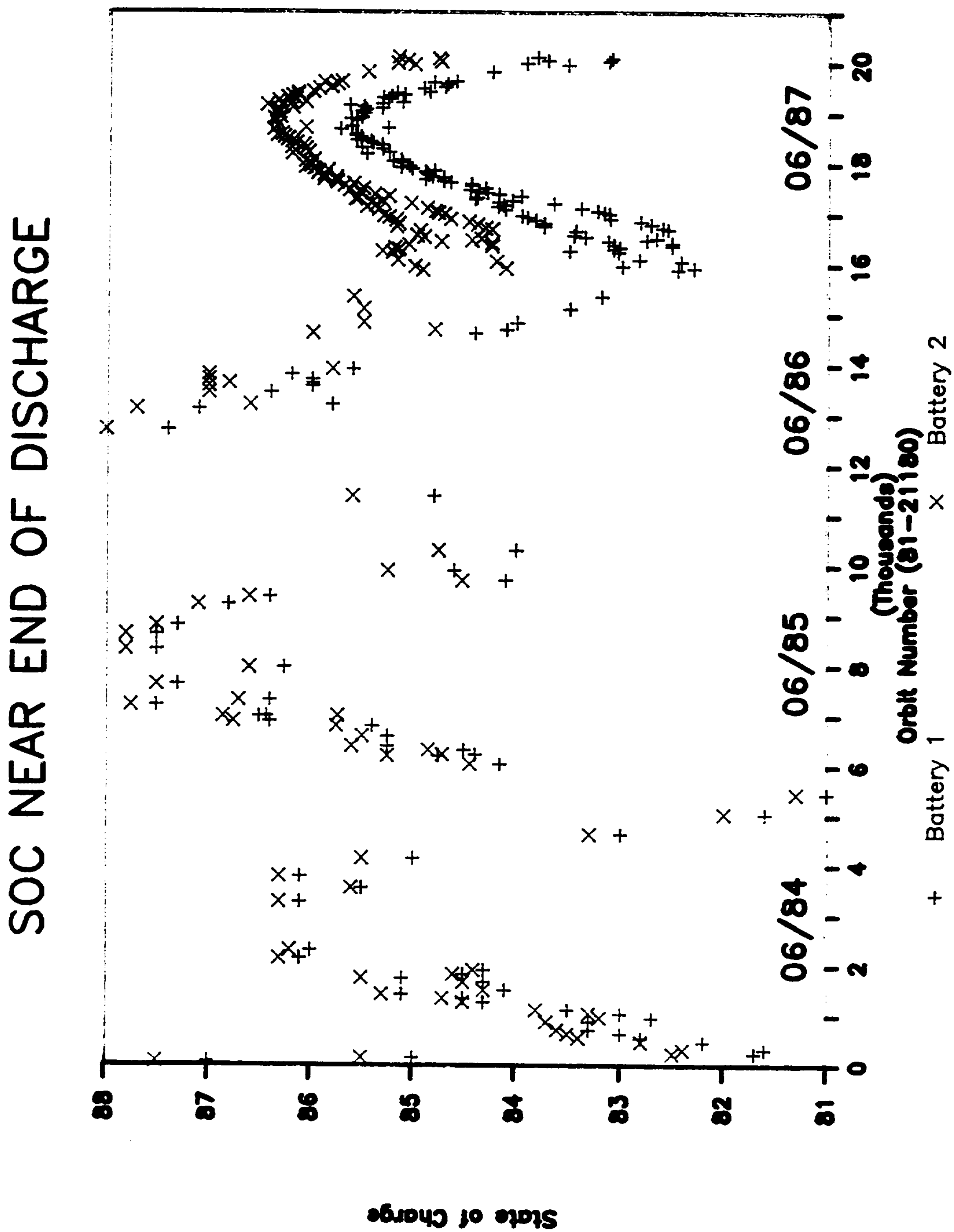
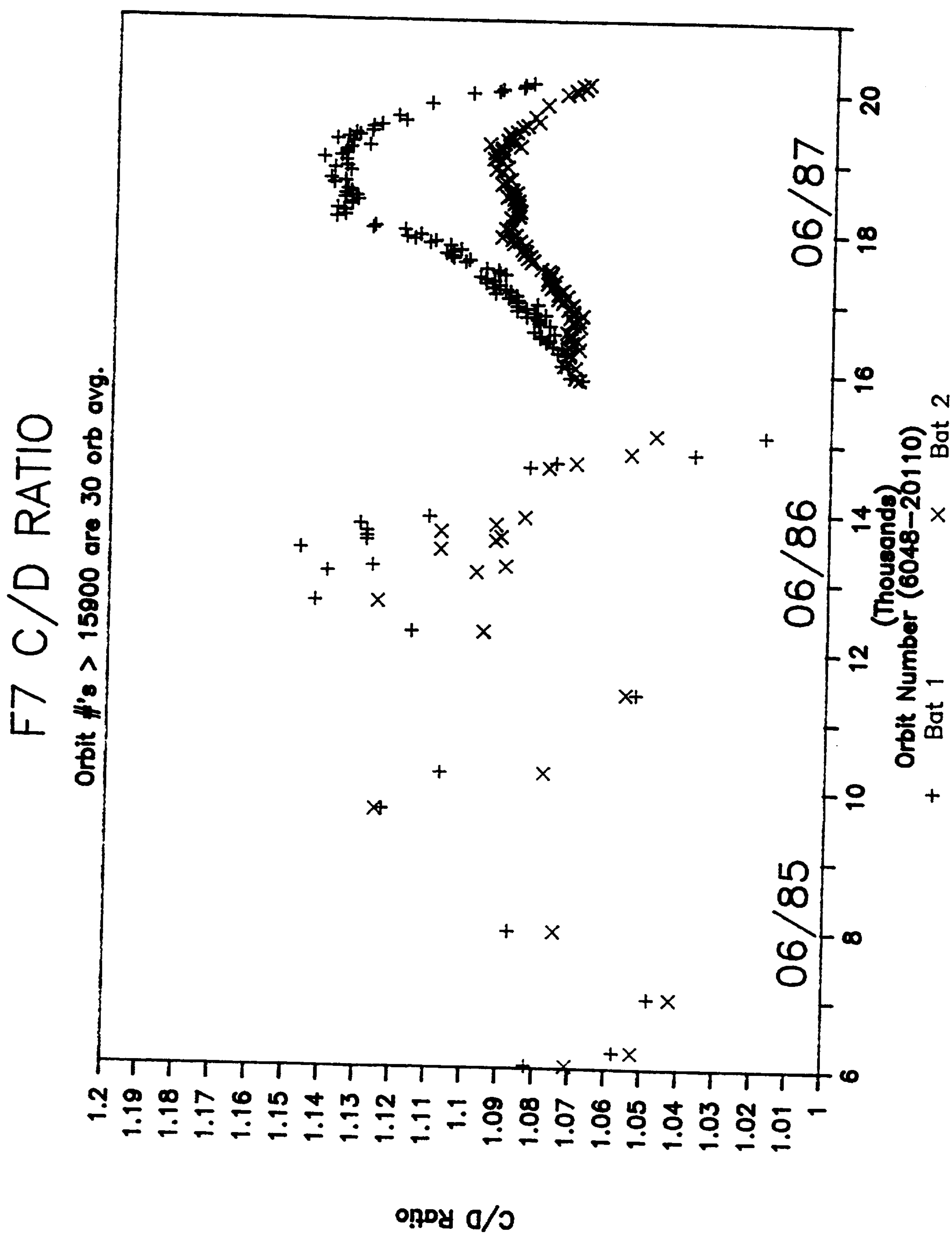


FIGURE 8. MATSUMOTO


F7 C/D RATIO
Orbit #'s > 15900 are 30 orb avg.
C/D Ratio
1.2
1.19
1.18
1.17
1.16
1.15
1.14
1.13
1.12
1.11
1.1
1.09
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1
6
8
10
12
14
16
18
20
06/85
06/86
06/87
Orbit Number (6048–20110)
(Thousands)
Bat 1
Bat 2

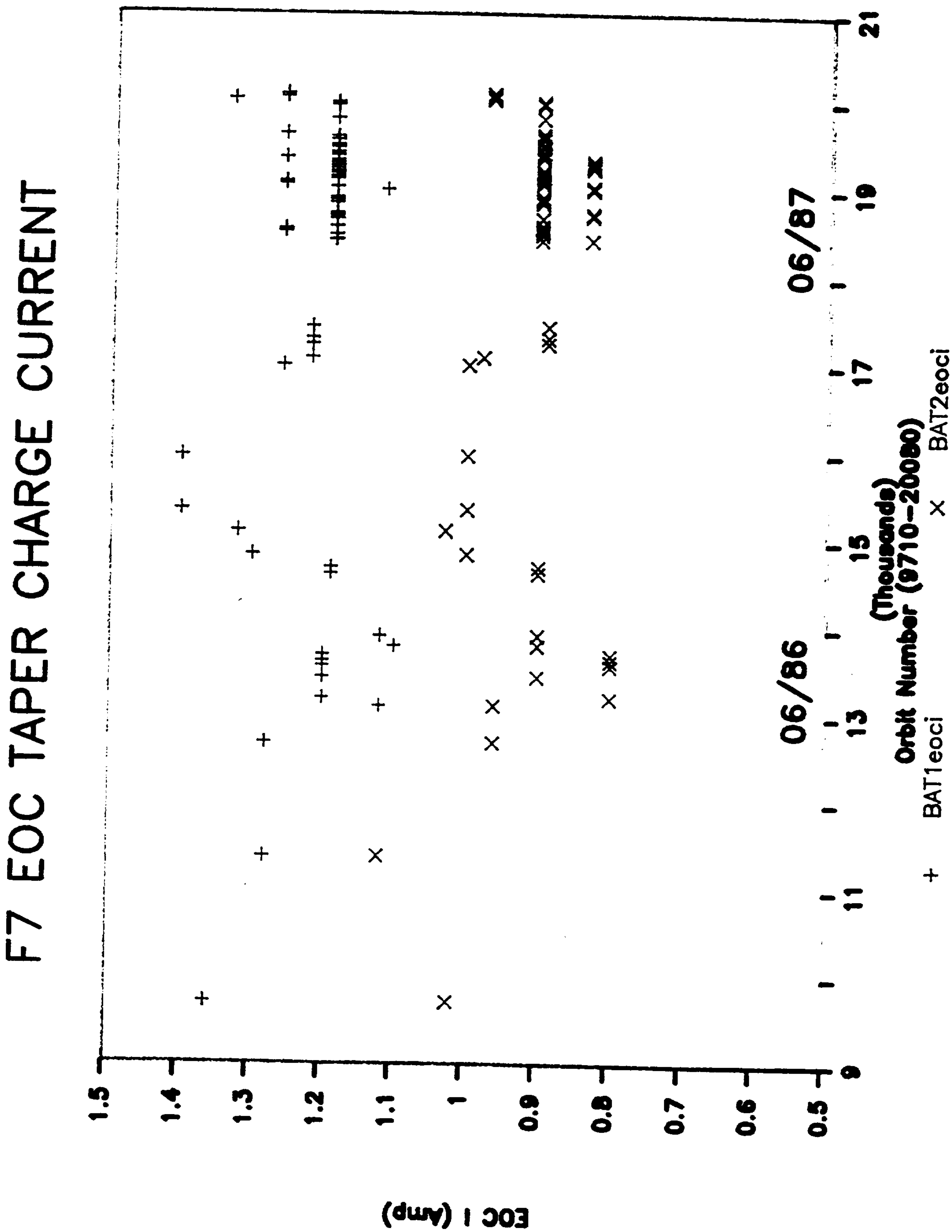


FIGURE 10. MATSUMOTO

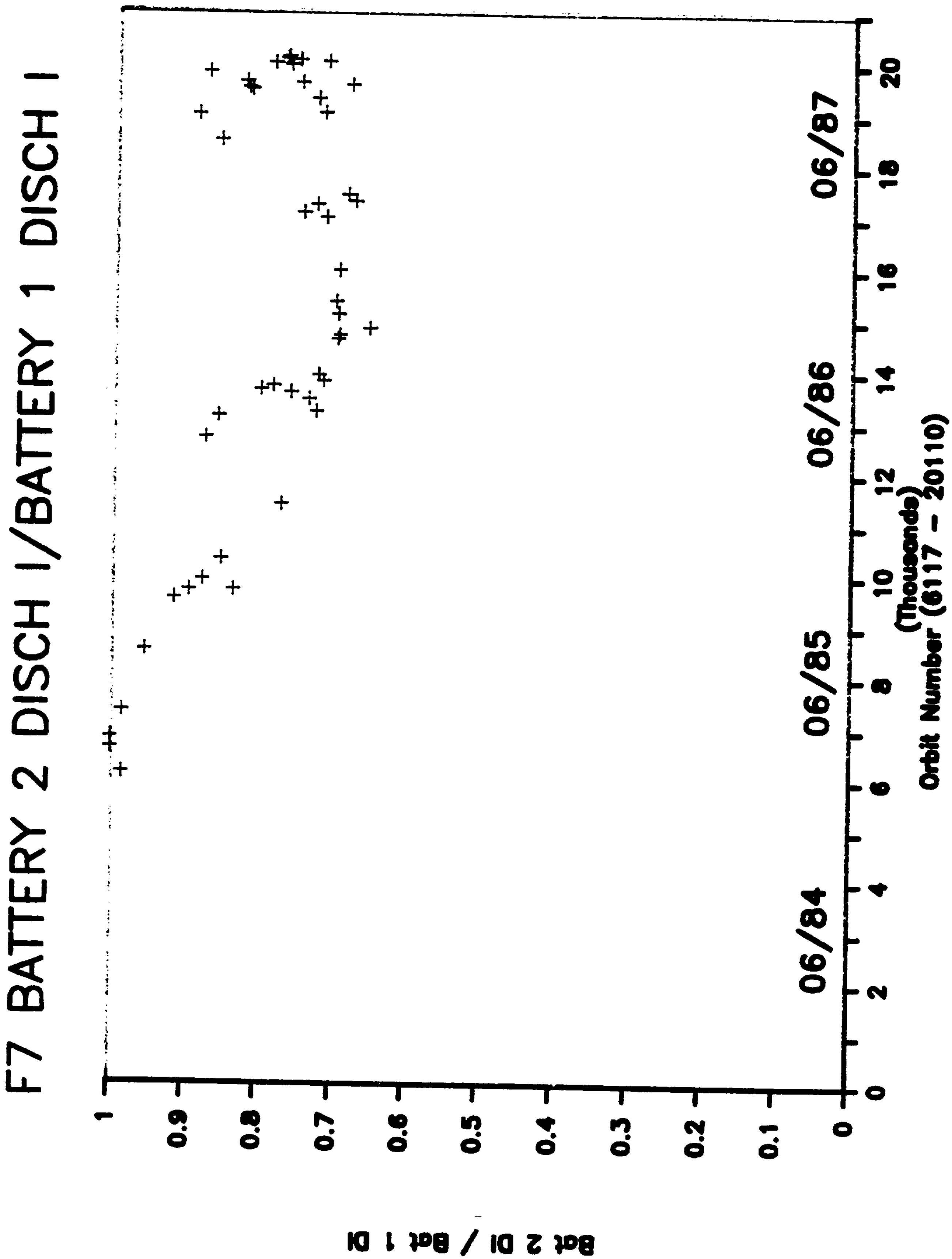


FIGURE 11 MATSUMOTO

SUMMARY OF BATTERY WINTER TO SUMMER TRENDS

- Battery minimum voltage increases
- Battery temperature decreases
- Minimum SOC increases (DoD decreases)
- C/D ratio increases
- Battery final taper charge decreases
- DoD differences between batteries decrease
- Differences between battery 1 and battery 2 discharge current decreases

FIGURE 12. MATSUMOTO

EFFECTS ON F7 BATTERY OPERATION AND LIFE

- Battery management
  - Can indicate seasonal adjustments to compensate for seasonal variations
  - Can provide for more optimal monitor/control with approaching end–of–life and heavier seasonal use
- Mission life:
  - Battery degradation = expected long term degradation + superimposed seasonal effects
  - Failure more likely in winter than in summer

FIGURE 13. MATSUMOTO

GENERAL USEFULNESS

- Well characterized behavior can lead to more accurate future predictions
- More optimized battery management
- Input will be required for long term autonomous operation

FIGURE 14. MATSUMOTO

SESSION IV

NICKEL HYDROGEN

Chairman: Dr. Lawrence Thaller, NASA/LeRC

"NiH_2 BATTERY RECHARGE MANAGEMENT FOR IN-ORBIT OPERATIONS"

ROBERT GREEN

At this point the meeting turned to presentations on Nickel Hydrogen batteries, and the chairman was Lawrence Thaller (NASA/LeRC). The first speaker of the NiH_2 program was Robert Green (GTE Spacenet) on "NiH_2 Battery Recharge Management for In-Orbit Operations." Green pointed out that his co-author is Marc Smith.

Green discussed autonomous recharge management for the NiH_2 batteries onboard the GSTAR and Spacenet Satellites. The satellite characteristics are shown in Green [Figures 4, 5, and 6] and the battery characteristics appear in Green [Figures 6 and 7]. Charge Rates, and Depth of Discharge design goal appear in Green [Figures 9, 10, and 11].

GTE Spacenet's goal was to get away from traditional "hands on" battery management, Green [Figures 13 and 14], and to devise a scheme whereby "daily wait until the last minute calculations are rendered obsolete."

The new plan calls for prediction of many variables and estimation of the discharge load using either previous eclipse season data or the spacecraft power budget (Green [Figure 16]). The new plan also eliminates computing accurate eclipse enter/exit times. As a result of calculations shown in Green [Figures 17,18,19, and 20] charge rates and recharge times were calculated as shown in Green [Figures 21,22, and 23]. Then a spacecraft command schedule could be generated for an entire eclipse season, and the daily task of calculating battery recharge could be eliminated (Green [Figure 23A]).

It was found that adequate battery recharge could be performed on all the GTE spacecraft throughout the eclipse season, using pre-eclipse-generated command sequences. (See Green [Figures 25, 26, and 27]).

Q. Dunlop (COMSAT): How do you do reconditioning?

A. We do not perform reconditioning it although we have the capability to do so.

Q. Mackowski (McDD): On the older system were you using onboard amp-hour integration? Does one spacecraft have bypass diodes and the other doesn't?

A. Everything was calculated on the ground. The battery design is the combined effort of GTE and the satellite manufacturer.

Q. Sullivan (APL): Why not use deep discharge reconditioning? Is it a reliability consideration?

A. Deep discharge reconditioning of NiH_2 batteries has no advantage in geosynchronous orbit.

Q. Bragg (JSC): How many spacecraft are we talking about?

A. There are four spacecraft in orbit now and three to come.

Q. Anjou (Intelsat): Did reconditioning have any effect on pressure?

A. Again, we do not perform reconditioning on any of our batteries at this time.

Q. Anjou (Intelsat): You may limit the pressure rise if you do it.

A. The battery design has been reported in the proceedings of the IECEC in 1984.

NICKEL-HYDROGEN BATTERY RECHARGE MANAGEMENT FOR IN-ORBIT OPERATIONS

ROBERT S. GREEN
AND
MARC A. SMITH
GTE SPACENET CORP.
MCLEAN, VA

FIGURE 1. GREEN

GTE SPACENET

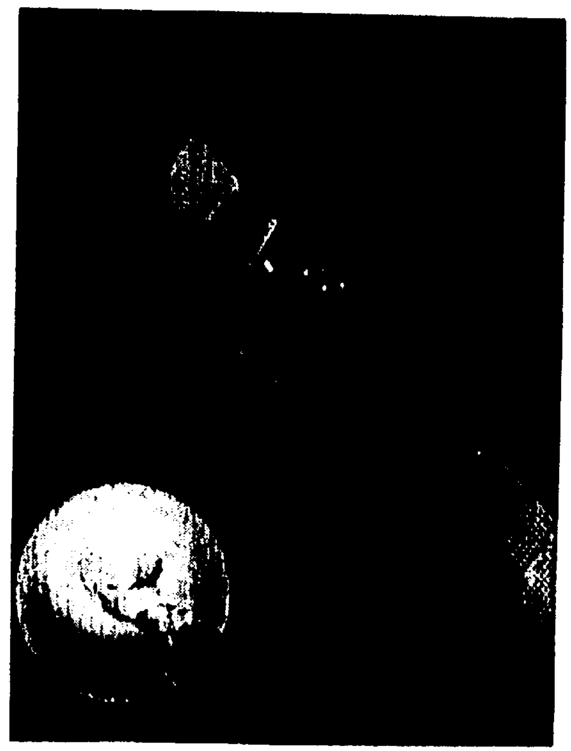


FIGURE 2. GREEN

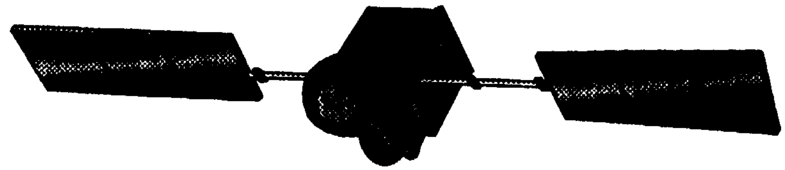
LAUNCH DATES

SPACENET I	May,84
SPACENET II	Nov,84
GSTAR I	May,85
GSTAR II	Feb,86
SPACENET IIIR	Dec,87 (Exp)
GSTAR III	May,88 (Exp)
GSTAR IV	89

All Launched Via Ariane ELV From
Kourou, French Guiana

FIGURE 3. GREEN

SPACENET SATELLITE



Satellite	Launch Dates	Orbit Location
SPACENET I	May, 1984	120° WL
SPACENET II	Nov, 1984	69° WL
SPACENET III	2nd Q '88	87° WL

Satellite Coverage		
Spacenet I	Spacenet II	Spacenet III
C-Band - 50 State	C-Band - CONUS & Puerto Rico	C-Band - CONUS & Puerto Rico
Ku-Band - CONUS	Ku-Band - CONUS	Ku-Band - East/West Spot Beams

Redundancy

High Power Amplifiers:

C-Band:
4 for 2

Ku-Band:
2 for 1

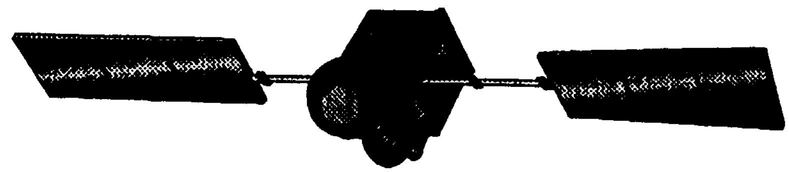
Transponder Configuration per Satellite

C-Band:
12 - 36 Mz Transponders Using 8.5 Watt Solid State Amplifiers
6 - 72 Mz Transponders Using 16 Watt Travelling Wave Tubes

Ku-Band:
6 - 72 Mz Transponders Using 16 Watt Travelling Wave Tubes

FIGURE 4. GREEN

GSTAR SATELLITES



Satellite	Launch Dates	Orbit Location
GStar I	May, 1985	103° WL
GStar II	February, 1986	105° WL
GStar III	4 Quarter 1987	136° WL

Satellite Coverage

14 Channels - CONUS-wide, or Individually Commandable to Eastern or Western Regional Beams

2 Channels - Combined CONUS, Alaska and Hawaii

GStar I and II Offer High EIRP Spot Beams

Redundancy

High Power Amplifiers:

20 Watt - 22 for 16 Ring Redundancy

27 Watt - 3 for 2

Transponder Configuration per Satellite

14 Channels - 54 Mz Transponders Using 20 Watt Amplifiers

2 Channels - 54 Mz Transponders Using 27 Watt Amplifiers

FIGURE 5. GREEN

GSTAR Satellites - Are Equipped With Three Parallel Connected 30 AH Nickel-Hydrogen Batteries

SPACENET Satellites - Are Equipped With Two Parallel Connected 40 AH Nickel-Hydrogen Batteries

FIGURE 6. GREEN

SPACENET NICKEL-HYDROGEN BATTERY

- 40 AH Nameplate Capacity
- 22 Cells Per Battery
- 2 Cells Per Battery Equipped With Strain Gauge Bridges
- Individual Cell Heater Strips-Redundant
- Individual Cell Reconditioning Resistors
- Individual Cell Bypass Circuitry

FIGURE 7. GREEN

GSTAR NICKEL-HYDROGEN BATTERY

- 30 AH Nameplate Capacity
- 22 Cells Per Battery
- 2 Cells Per Battery Equipped With Strain Gauge Bridges
- Individual Cell Heater Strips
  - Redundant
- Individual Cell Reconditioning Resistors
- Cell Voltage Monitors

FIGURE 8. GREEN

CHARGE RATES

- C Represents Nameplate Capacity
- C/10 (C/13 For Spacenet) is Available Only Through V-T Charge Circuitry and is Utilized One Battery at a Time
- Low Rate Trickle (LRT) is Available Through a Resistor Network - Thus A Slightly Variable Rate Dependent on Battery Voltage

FIGURE 9. GREEN

AVAILABLE CHARGE RATES

Available Charge Rate	GSTAR	SPACENET
C/10	3.0A	N/A
C/13	N/A	3.0A
C/20	1.5A	2.0A
C/30	1.0A	1.3A
C/60	0.5A	.67A
Low Rate Trickle (LRT)		
(1 Battery)	.35A	.35A
(2 Battery)	.18A	.18A
(3 Battery)	.12A	———

FIGURE 10. GREEN

DEPTH OF DISCHARGE DESIGN GOAL

- 60 Percent of Measured Capacity at Actual Operating Temperatures

- Assuming the Battery Yields 110 Percent of Nameplate Capacity, Design Maximum DOD Is at 66 Percent of Nameplate

FIGURE 11. GREEN

BATTERY LOADING

- Worst Case Load at Beginning Of Life Translates to Approximately 52 Percent DOD, Or 14 Percent Margin

- With Another 4 Percent Added Due To Good Spacecraft Thermal Management, --- 18 Percent Margin

- Maximum DOD Occurs Only at Equinox and Occasional North/South Stationkeeping, DOD is Less Than 45 Percent

FIGURE 12. GREEN

TRADITIONAL BATTERY MANAGEMENT

1. Calculate (Integrate) Ampere-Hours Removed (AHo)

2. Choose a Recharge Fraction (RR) And a Charge Rate (Ic) Based on Battery Temperatures

3. Plug in

$$\frac{(AHo) \times (RR)}{(Ic)} = T$$

Where T = Hours of Recharge at Ic

FIGURE 13. GREEN

TRADITIONAL BATTERY MANAGEMENT (CON'T)

- Actual AH_O is Best Done By Computer Real-Time
- For Batteries Using Radiative Thermal Design Where Overcharge Generates Excessive Heat, the Recharge Time May Need to be Trimmed Real-Time to Prevent Overheating
- This System Becomes Complex, Cumbersome, and an Inefficient Use of Resources When Controlling Multiple Satellites

FIGURE 14. GREEN

GOAL: Devise a Scheme Whereby Daily "Wait Until the Last Minute" Calculations Are Rendered Obsolete

FIGURE 15. GREEN

THE NEW PLAN

- Many Variables That Made Traditional Battery Management Tedious Can Be Predicted
- The Discharge Load Can Be Estimated Using Either the Previous Eclipse Season Data or the Spacecraft Power Budget
- Accurate Eclipse Enter/Exit Times That Were Predicted based On Spacecraft Position in the Box Are No Longer Required

FIGURE 16. GREEN

ECLIPSE DURATION (CON'T)

- The Daily Umbral Duration (T u) Is Calculated Using the Formula For an Eclipse With 67.5 Minutes As the Maximum Duration And 43 Days as the Total Length of the Season. The Total Removed During Umbra is

$$AHu = (T\ u) \times (ID)$$

- The Total Ampere-Hours Removed (AH T) is

$$AH\ T = AHp + AHu$$

FIGURE 17. GREEN

ECLIPSE DURATION

- The Total Penumbral Portion is Assumed to be a Constant Six Minutes For All Spacecraft. Penumbral Discharge is Averaged, Based on Previous Eclipse Data. Since Penumbral Shadow Versus Time Approximates a Sine Wave And the Duration is an Assumed Six Minutes, the Total Ampere-Hours Removed During Penumbra is

$$AHp = \frac{.2 \times ID}{\pi}$$

FIGURE 18. GREEN

RECHARGE TIME - SPACENET

- The Recharge Time (T) for a Spacenet Battery is Given as

$$T = \frac{12 \times (AH \quad T)}{2 \text{ Ampere}} - 1 \text{ Hour}$$

- Where 12 is the Recharge Fraction
  2 Ampere is the Normal Charge Current (C/20)
  1 Hour is the Thermal Cutback Factor

FIGURE 19. GREEN

THERMAL CUTBACK FACTOR

- In Overcharge the Increase in Temperature is Greater Than the Heat Rejection Capability of the Battery

- A One Hour Thermal Cutback Factor is Chosen From Analysis of Previous Eclipse Season Data

- This Fixed Backoff is Utilized Throughout the Eclipse Season

FIGURE 20. GREEN

DAILY CHARGE RATE PROFILE FOR SPACENET

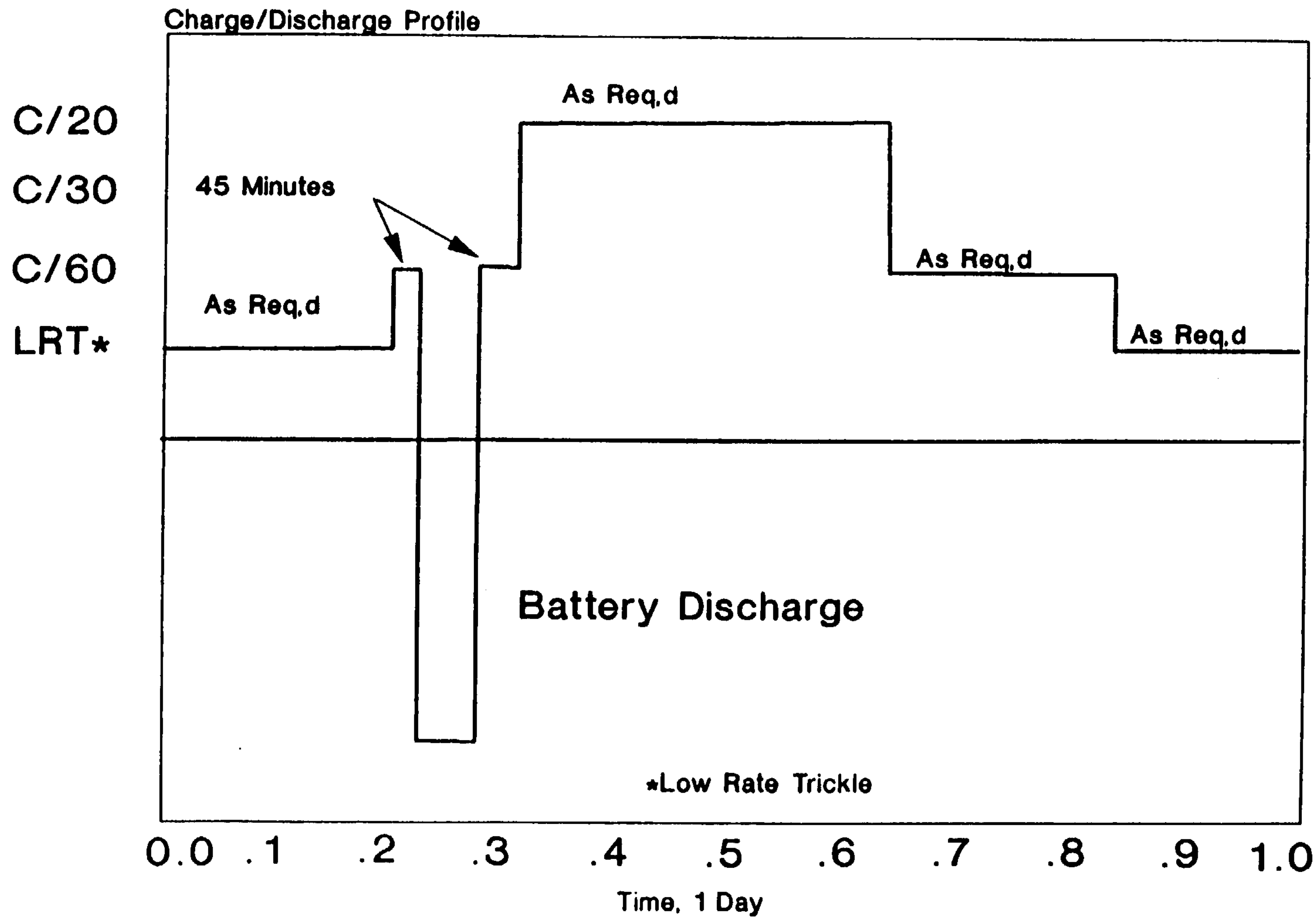


FIGURE 21. GREEN

RECHARGE TIME - GSTAR

- The Recharge Time (T) for a GSTAR Battery is Given as

$$T = \frac{1.1 \times (AH \quad T)}{1.5 \text{ Ampere}}$$

Where 1.1 is the Recharge Fraction
1.5 Ampere is the Normal Charge Current (C/20)

- The 1.1 RR Incorporates the Thermal Cutback Factor

FIGURE 22. GREEN

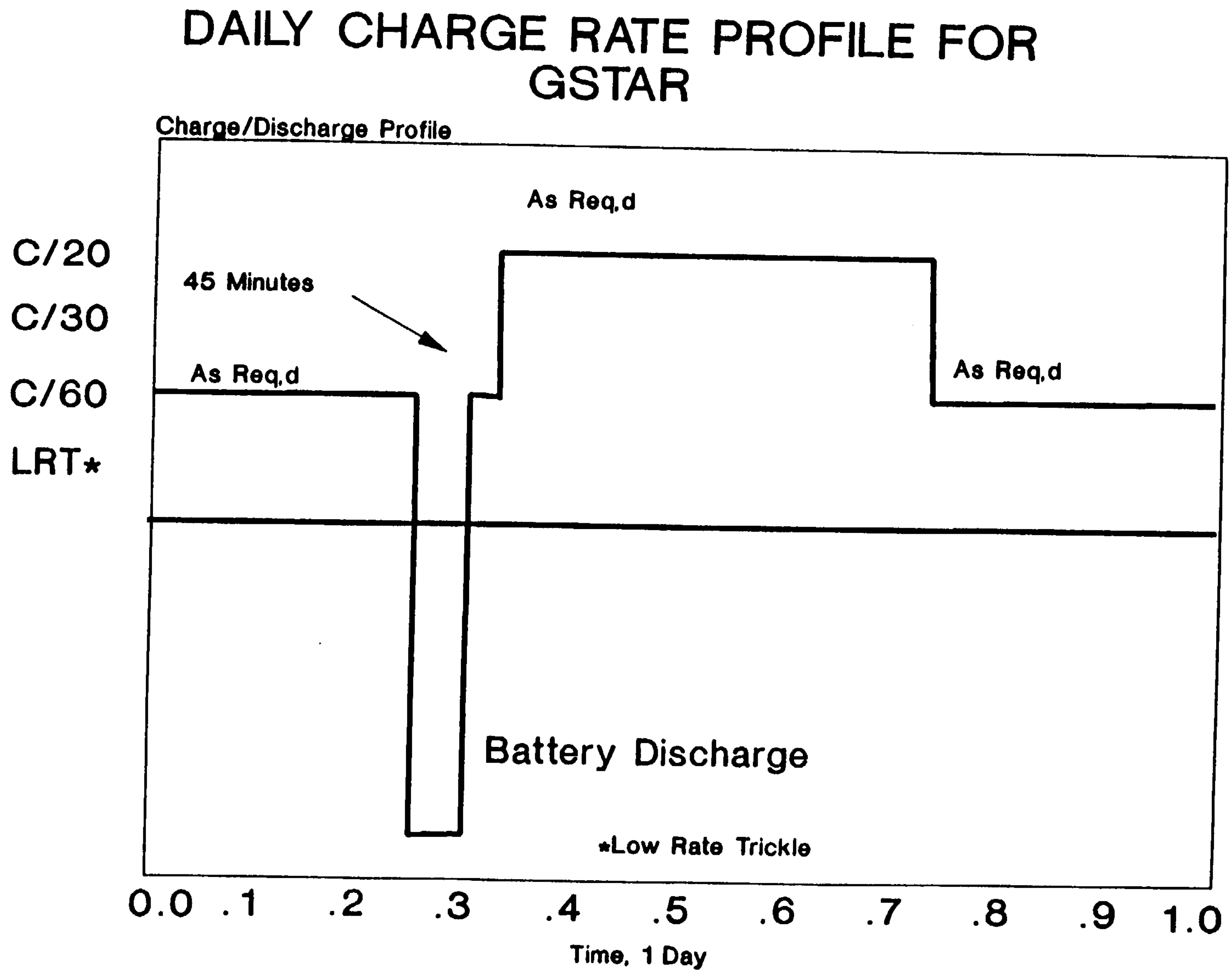


FIGURE 23. GREEN

BATTERY CHARGE COMMANDS

- A Spacecraft Command Schedule Can Be Generated For the Entire Eclipse Season From These Predictions and Estimates. The Daily Task of Calculating Battery Recharge is Eliminated

- The Operations Engineer Need Only Review the Flight Telemetry Periodically to Verify That the Spacecraft Load Has Not Changed And Insure Full Battery Recharge

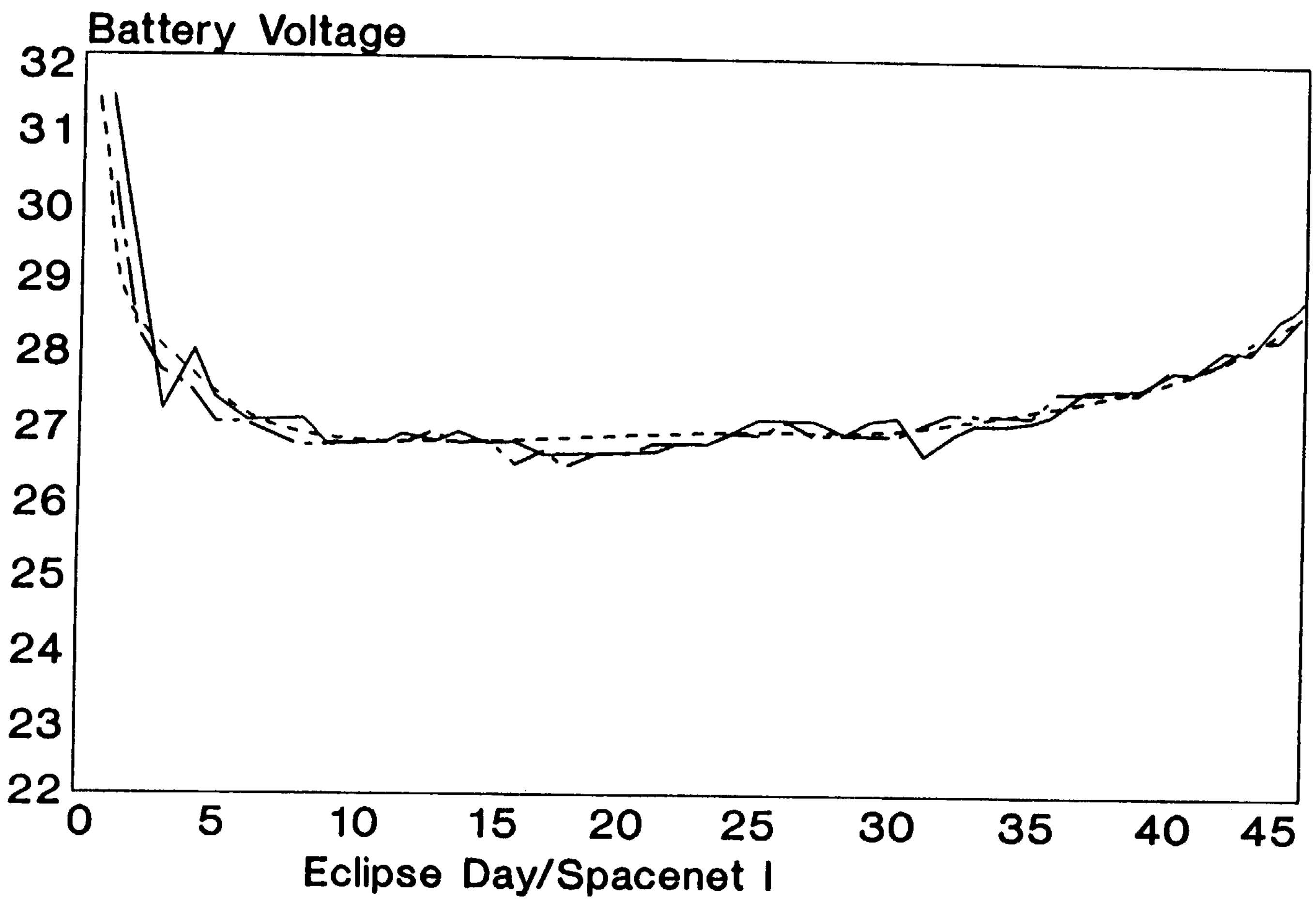
FIGURE 23A. GREEN

CONCLUSION

- The Recharging of Batteries During Eclipse Season Has Been Greatly Simplified
- Battery Recharge Parameters Have Been Indentified And Command Lists Can Be Generated Prior to the First Days of Shadow
- Adequate Battery Recharge Throughout the Eclipse Season Using Pre-eclipse Generated Command Sequences Has Been Demonstrated on All GTE Spacecraft

FIGURE 24. GREEN

END-OF-DISCHARGE VOLTAGE VS
ECLIPSE DAY



Fall 85 —·—·—   Fall 86 ———   Fall 87 - - - - -

GTE Spacenet

FIGURE 25. GREEN

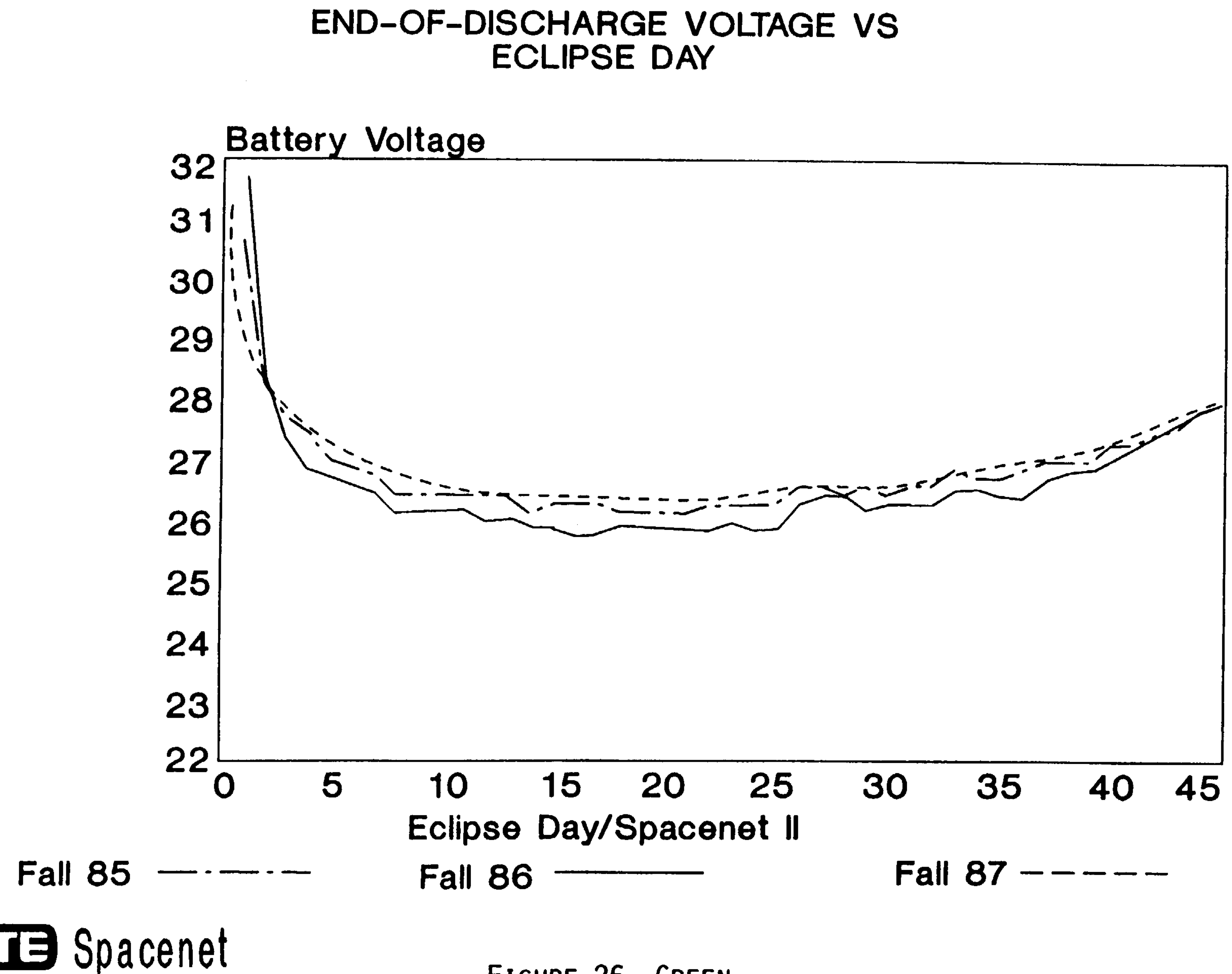
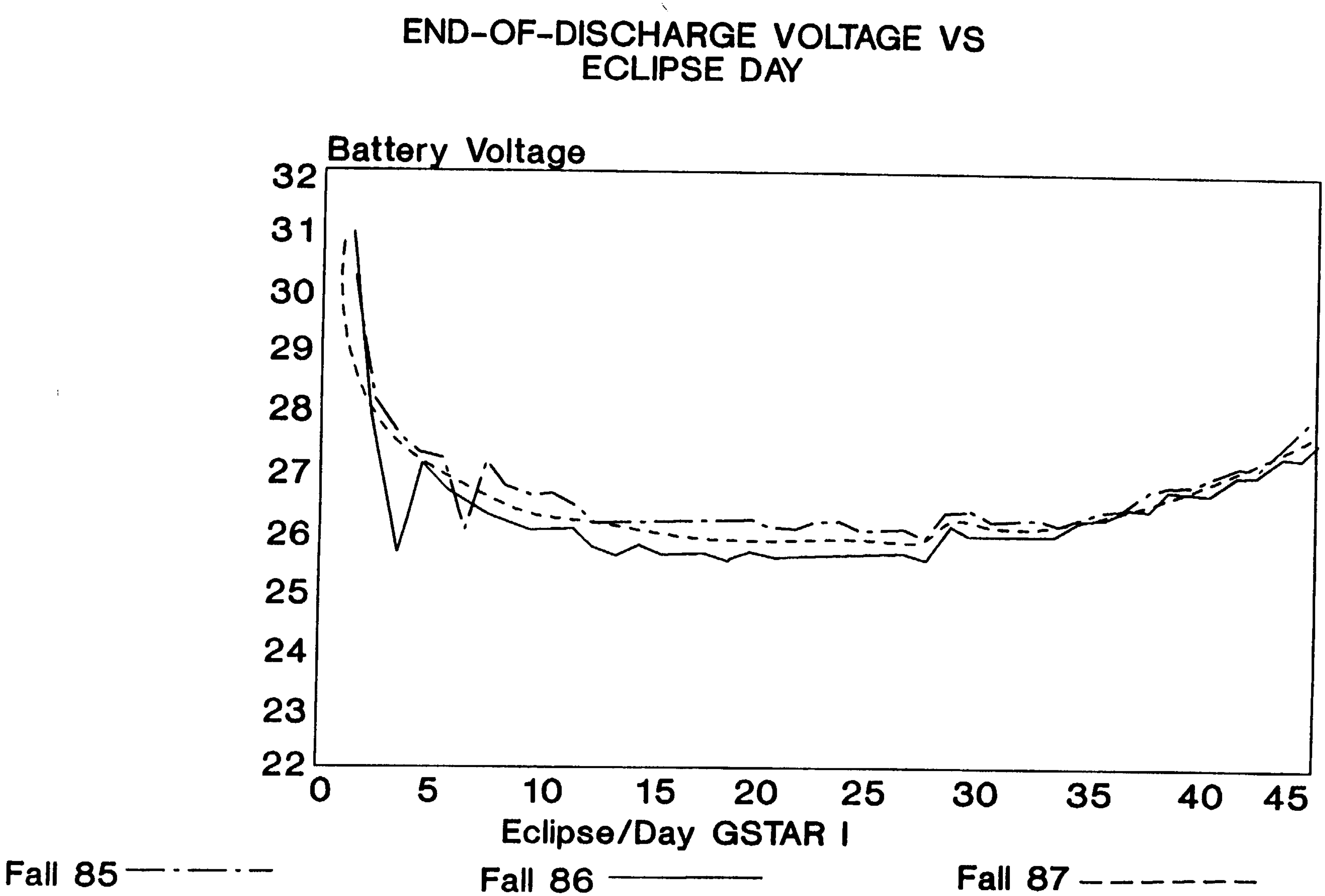


FIGURE 26. GREEN



GTE Spacenet

FIGURE 27. GREEN

"LIFE-TEST RESULTS OF THE INTELSAT-V NiH_2 BATTERY"

RON HUDAK presented by CHARLES KOEHLER

Charles Koehler was introduced as the substitute for Ron Hudak (Ford Aerospace) speaking on "Life-test Results of the Intelsat-V NiH_2 Battery."

Twenty seven cells are connected serially in a battery with bypass diodes and a strain gauge (Hudak [Figure 2]).

The first launch, in May 1983, demonstrated commercial communications satellite use of the NiH_2 battery.

There was a fairly constant EOD voltage over 18 seasons. EOC temperatures were tested at 10 degrees C chamber temperatures and the batteries achieved maximum temperatures of 15 to 20 degrees C. EOD temperatures were similar. Reconditioning was performed with a 50 ohm resistor. Performance was fairly stable at 33/34 amp-hours (Hudak [Figure 3]).

As a result of life testing for the equivalent of over 9 orbital years the conclusion is that 70 percent DOD operation is very feasible--it is a safe level of operation to use (Hudak [Figure 8]). (This is a requirement for INTELSAT-V geosynchronous operation.)

Q. Youngblood (GE Americom): Was the increase in capacity parallel to the increase in pressure?

A. We have seen an upward trend in pressure over the duration of the test.

Q. Dunlop (Comsat): The orbital data for Intelsat V shows that reconditioning capacity is fairly stable--it is not increasing. There is a small pressure rise with time. We may report the pressure rise vs time next year. The rate of change of "pressure" is used to terminate the charging in the Sandia program.

Q. Broderick (GTE): Does reconditioning improve the pressure rise? Can you explain this?

A. [British speaker]: The increase of pressure without an increase in capacity is bad. Reconditioning limits the pressure rise due to corrosion. A pressure rise of 15 to 25 psi has been observed with reconditioning. Without reconditioning you'd see double that on a yearly basis.

Q. ________ : What's the phenomenon?

LIFE TEST RESULTS

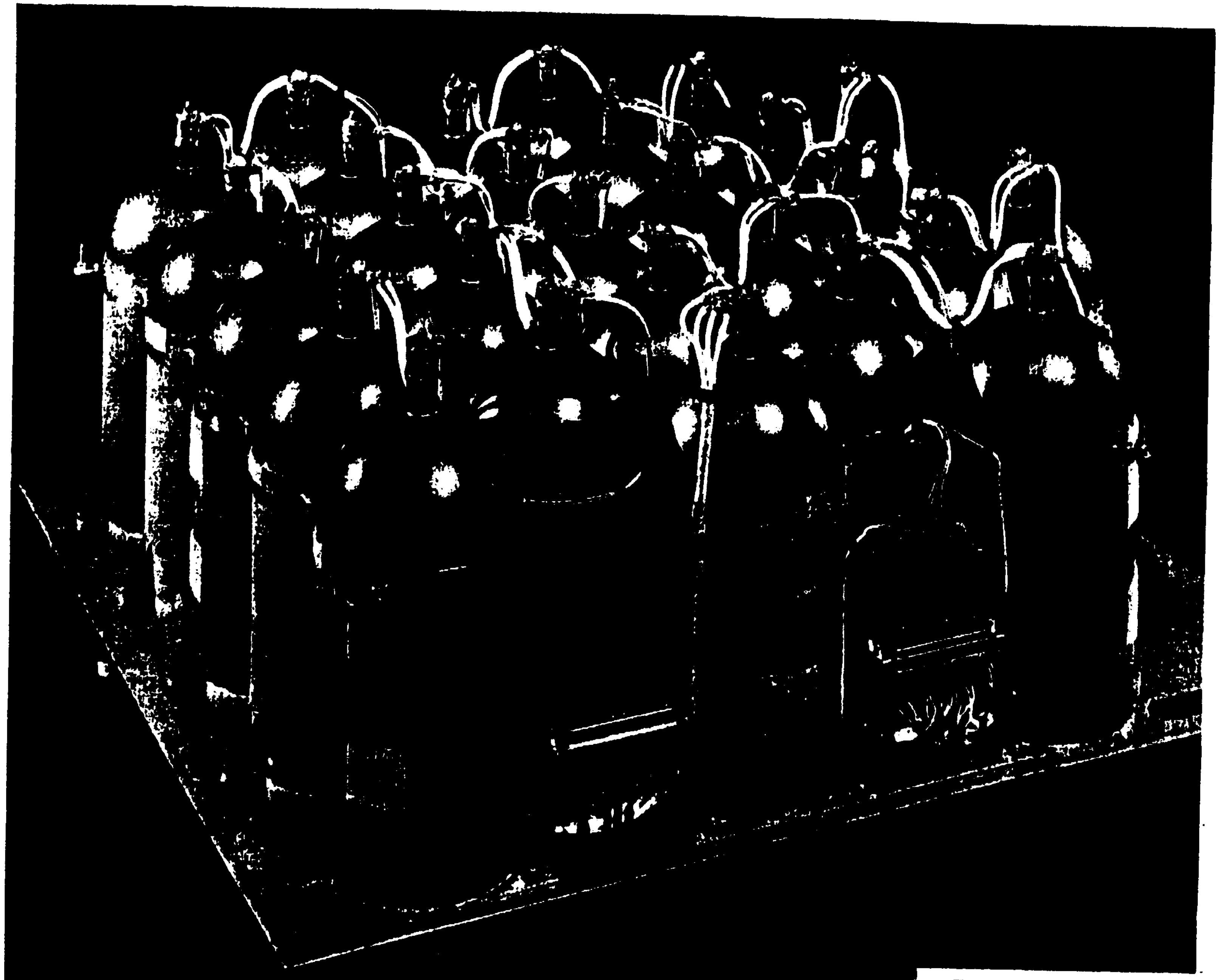
OF THE

INTELSAT V NICKEL – HYDROGEN BATTERY

RONALD E. HUDAK

PRESENTED BY:
C. W. KOEHLER

Ford Aerospace &
Communications Corporation



Ford Aerospace & Communications Corporation

INTELSAT V Ni-H2 BATTERY

FIGURE 2 [illegible]

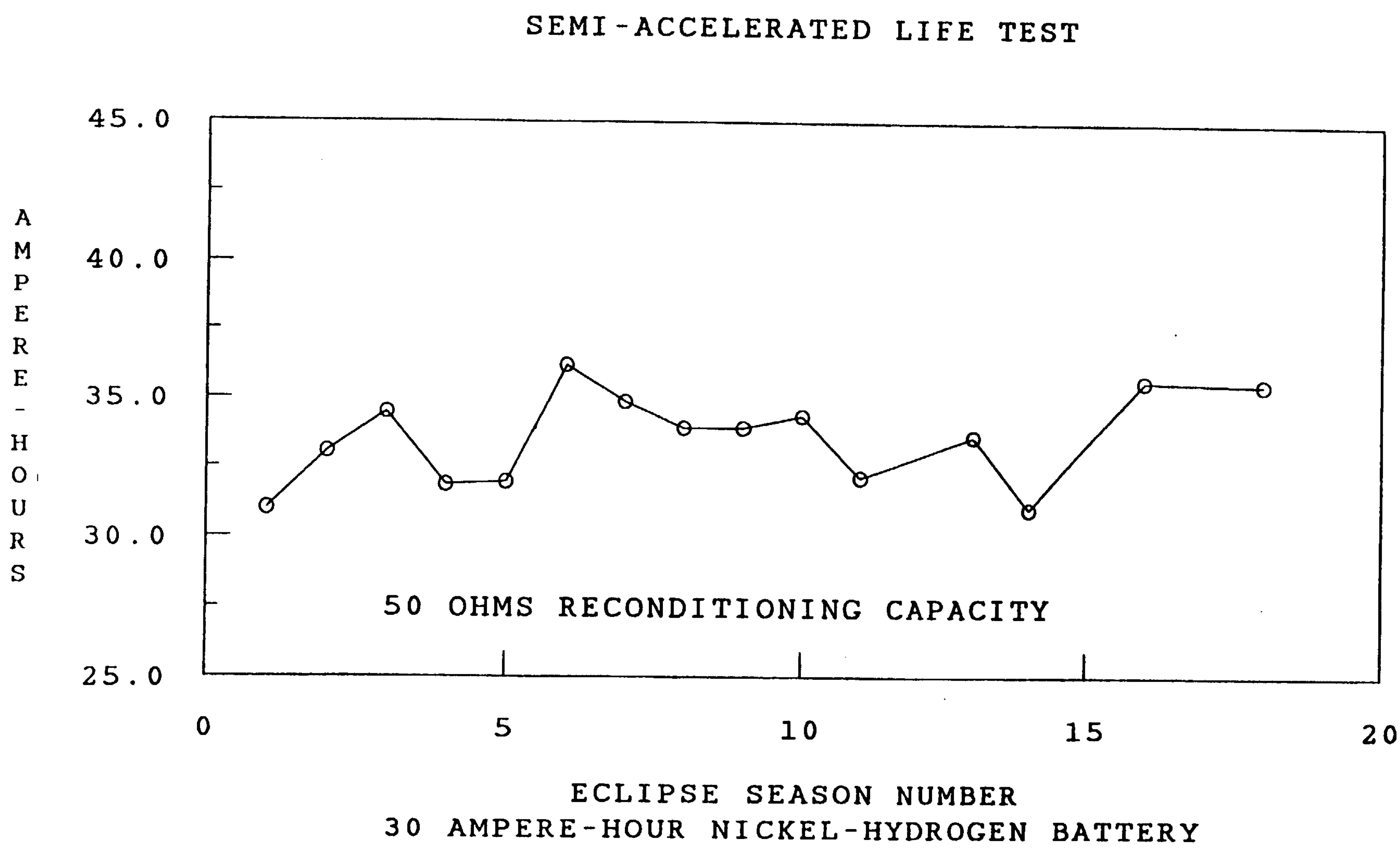


FIGURE 3. HUDAK RECONDITIONING DISCHARGE CAPACITY

Ford Aerospace & Communications Corporation

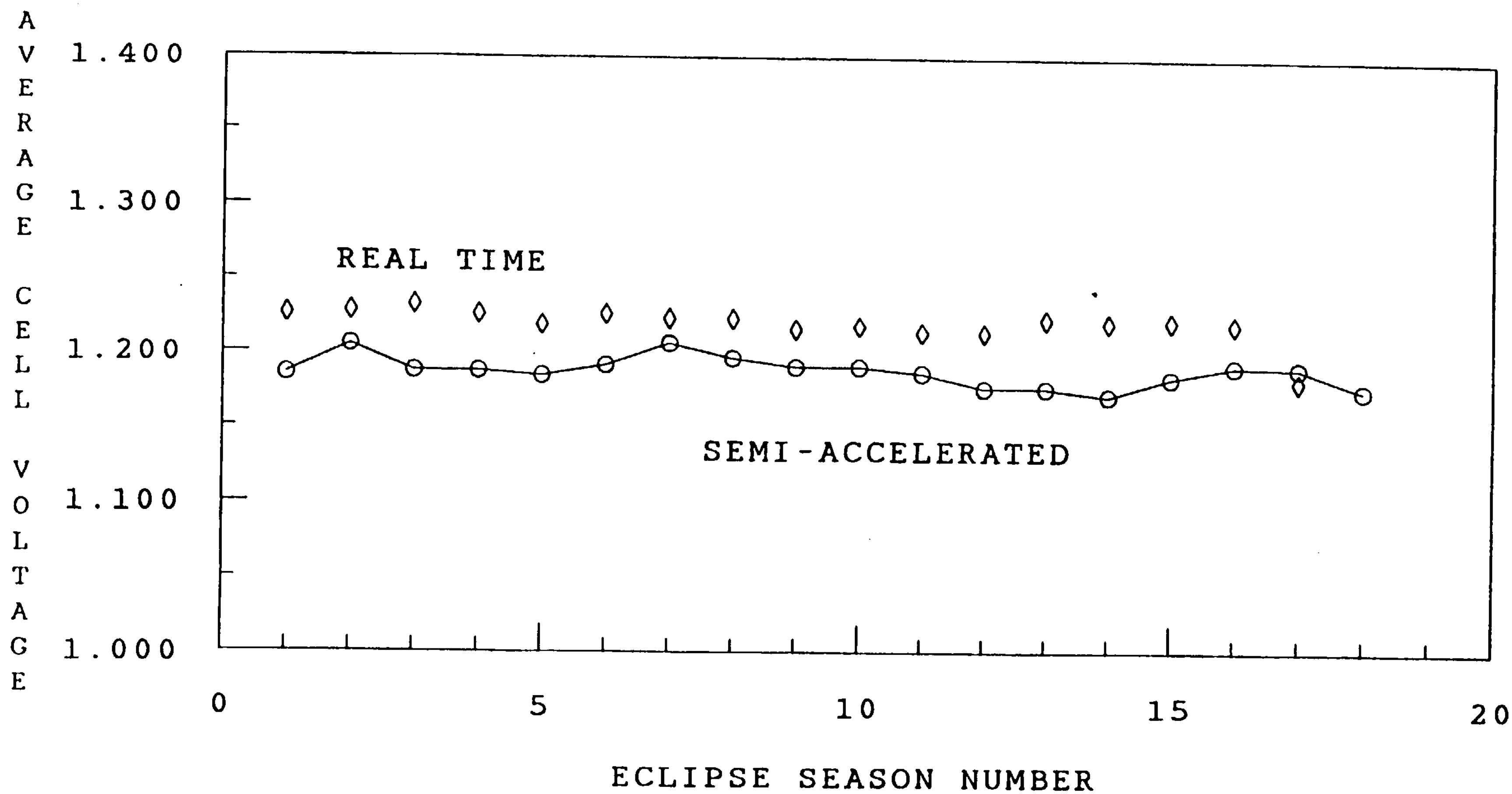


FIGURE 3 Average End-of-Discharge Cell Voltage at 60% DOD

FIGURE 4. HUDAK

Ford Aerospace & Communications Corporation

C-5

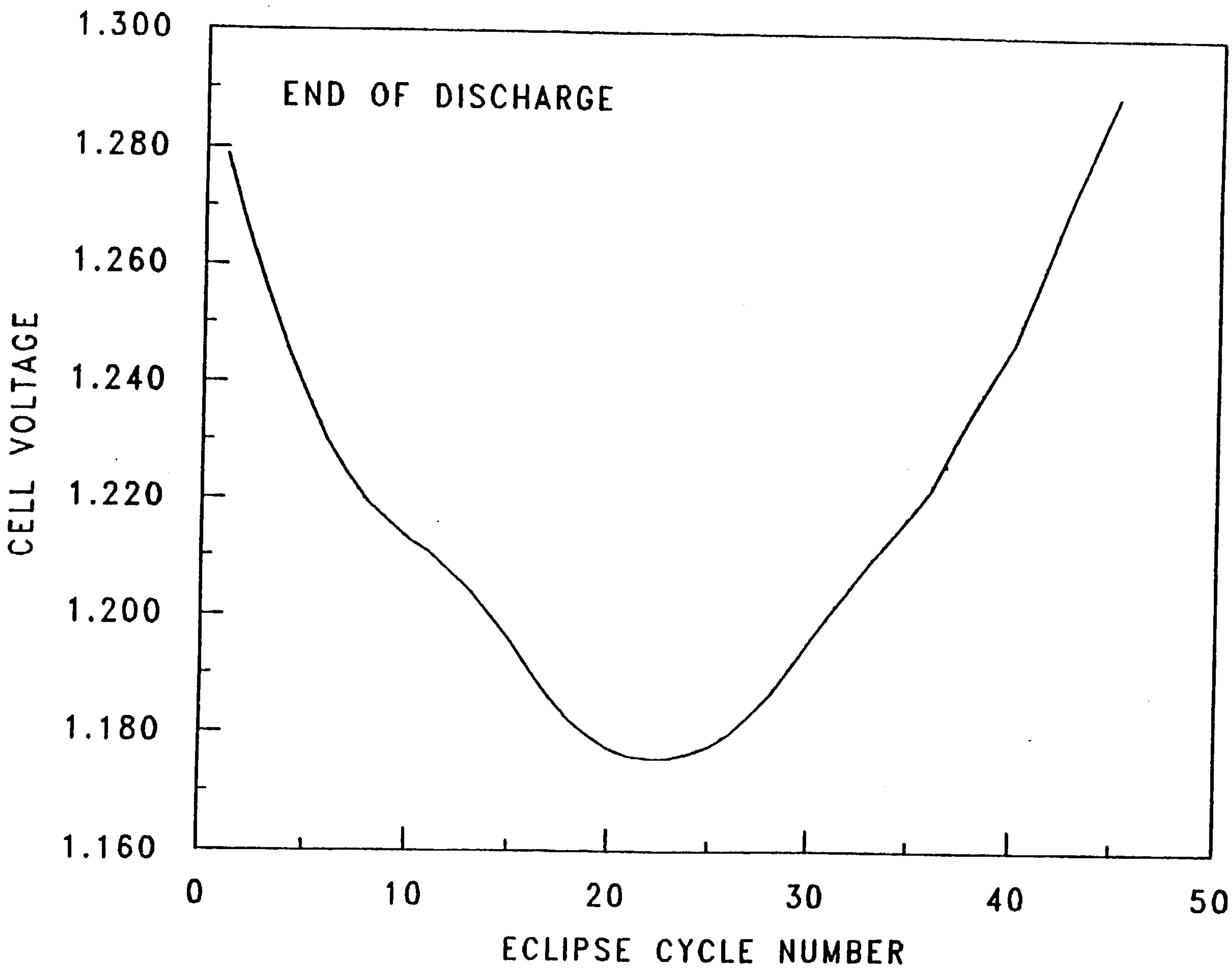


FIGURE 4 Average End-of-Eclipse Cell Voltage at Season 18

Ford Aerospace & Communications Corporation

FIGURE 5. HUDAK

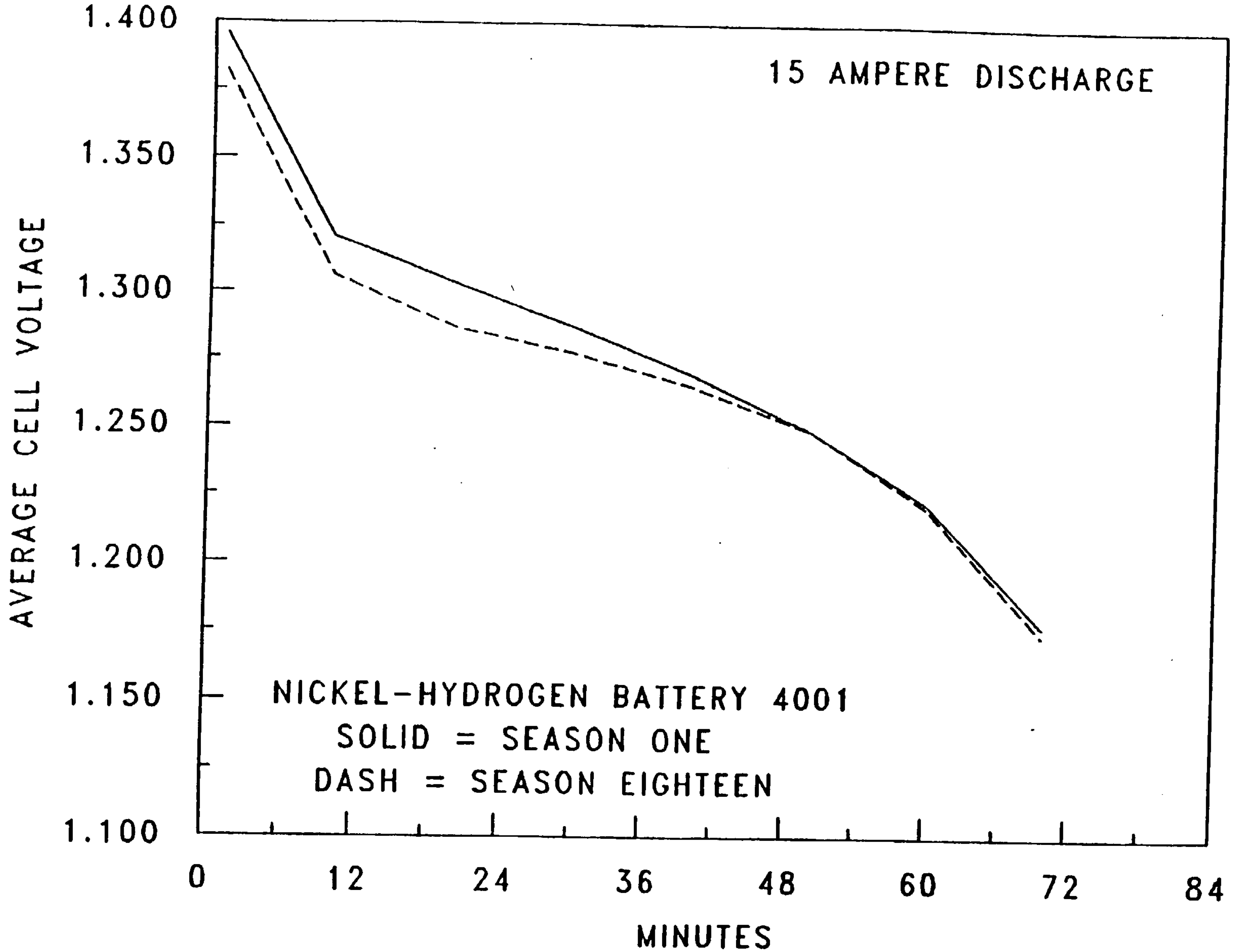


FIGURE 5 Typical Cell Discharge Voltage During 72 Minutes Eclipse

Ford Aerospace & Communications Corporation

FIGURE 6. HÚDAK

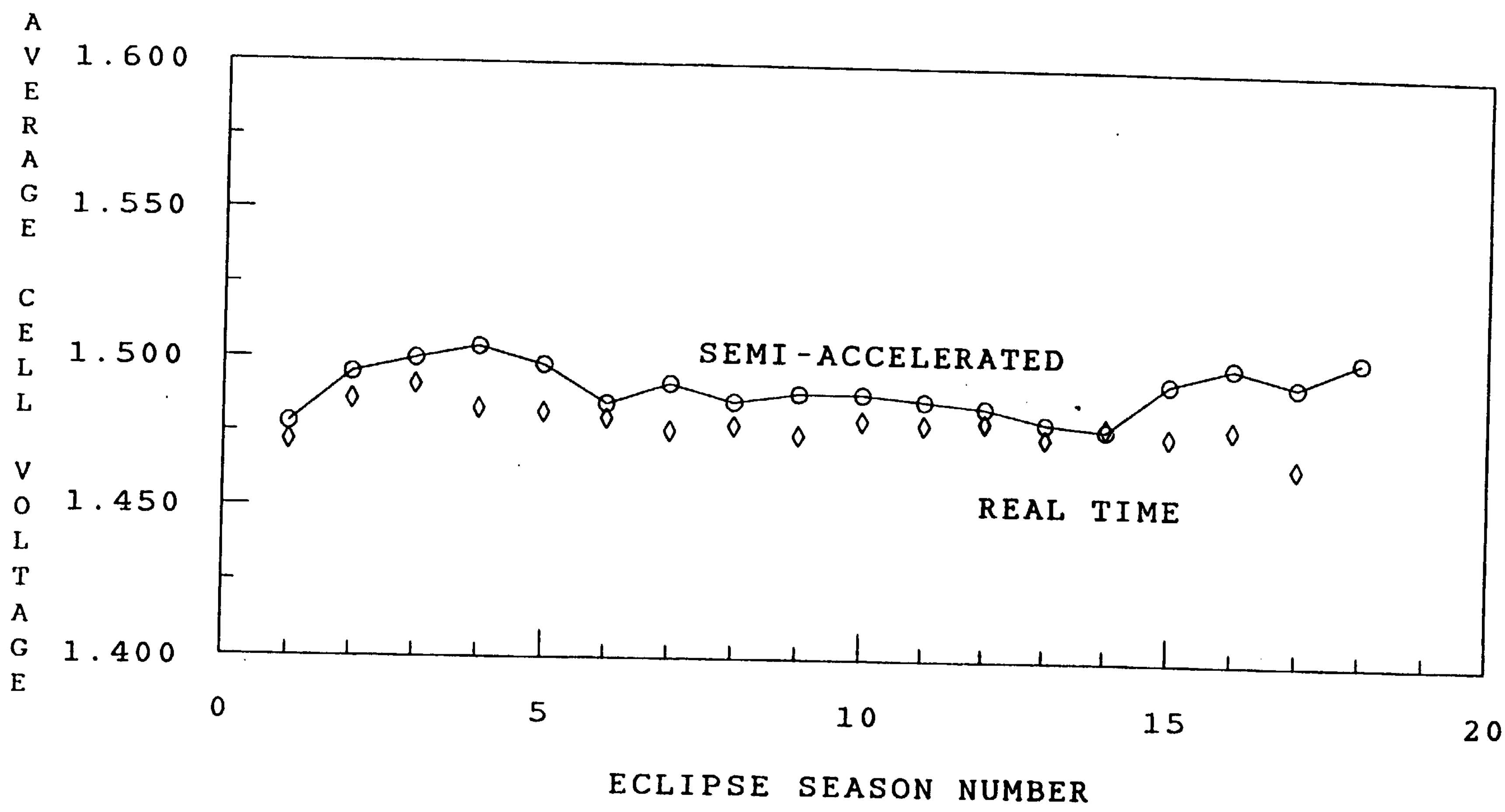


FIGURE 7. HUDAK AVERAGE END-OF- CHARGE VOLTAGE

Ford Aerospace & Communications Corporation

CONCLUSIONS

- Life Test ran for equivalent of nine orbital years
- Charge and Discharge Voltage performance stable for duration of test
- Ampere-Hour Capacity -- showed improvement with cycling
- Results comparable to Real Time and Orbital flight results
- Test supports INTELSAT-V Geo-synchronous operating requirement of seven years at 70% DOD

FIGURE 8. HUDAK

Ford Aerospace & Communications Corporation

LIFE TEST RESULTS OF THE INTELSAT-V NICKEL-HYDROGEN BATTERY

Ronald E. Hudak

Ford Aerospace & Communications Corporation
Western Development Laboratories
Palo Alto, California 94303

ABSTRACT

The electrical power subsystem for the INTELSAT-V communication satellite contains two nickel-hydrogen (Ni-H2) batteries (Figure 1) for energy storage, full eclipse operation capability and peak power operation exceeding solar array capability. The 27-cell battery assemblies have a nameplate capacity of 30 ampere-hours and are designed for a maximum depth-of-discharge of 70% over a mission life of seven years. A complete description of the battery, it's operating modes and the cell design is given in Reference 1. This battery design has now been flown on six INTELSAT-V spacecraft to date, sucessfully accumulating 33 battery-years of on-orbit operational performance. Flight model 6, launched in May, 1983, was the first INTELSAT spacecraft to be launched with the nickel-hydrogen battery which is now the battery system used on the remainder of the 15 satellite series. Two more satellites were launched with this battery system. Due to launch vehicle anomalies these satellites did not achieve geosynchronous orbit and are not operational. INTELSAT-V is the largest communications satellite now in operation for the International Telecommunications Satellite Organization (INTELSAT) and is built by an international team of contractors headed by Ford Aerospace & Communications Corporation (FACC). This paper summarizes the results of the semi-accelerated life test being conducted at FACC on the Ni-H2 battery.

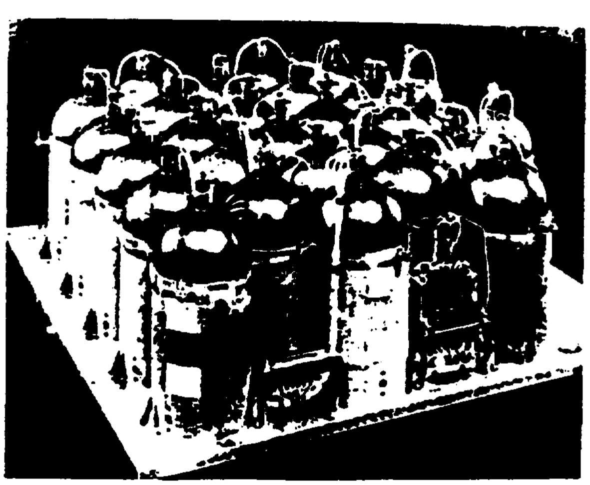


Fig. 1 INTELSAT-V NICKEL-HYDROGEN BATTERY.

LIFE TEST REGIME AND CONDITIONS

The semi-accelerated life test results in approximately six eclipse seasons per calendar year. Each eclipse season is simulated on a real time basis while the usually long solstice period is shortened to two weeks. During the solstice period a reconditioning cycle is performed using a 50 ohm resistive load and after every other season a capacity cycle is performed at 15 ampere (A) constant current discharge.

The daily eclipse consists of a 15A discharge varying from a minimum of 18 minutes to a maximum of 72 minutes. The maximum discharge corresponds to 60% depth-of-discharge (DOD), and is representative of normal on-orbit operation. Recharge is at the full rate of 2.86A followed by trickle charge at 0.96A and all charging is bi-sequenced at five minutes on/five minutes off. The recharge ratio at the full-charge rate is 1.15. The life test is being conducted at a nominal temperature of 10 degrees centigrade and the temperature is controlled by an environmental control chamber. Electrical control is achieved by dedicated test equipment, and cycling continues almost uninterrupted. Forty-five daily eclipse cycles constitute one eclipse season; eighteen eclipse seasons have been accumulated through October, 1986.

Prior to battery assembly the battery cells underwent cell validation testing and these test results were used for battery cell matching. Following assembly, the battery underwent acceptance testing, and was assigned to life test cycling. The baseline capacity measured at the end of acceptance was 32.85 ampere-hours. The battery was charged and the first eclipse cycle was initiated in November, 1982.

TEST RESULTS

The semi-accelerated life test of the INTELSAT-V battery design has successfully completed eighteen seasons of cycling with nearly undetectable degradation.

Figure 2 shows seasonal capacity measurement using the 50 ohm resistive reconditioning load to a nominal voltage cutoff of 27v battery or 0.7v cell as employed on the INTELSAT-V spacecraft. Variations in measured capacities are due to the actual cutoff voltage of each reconditioning cycle and are not due to changes in performance.

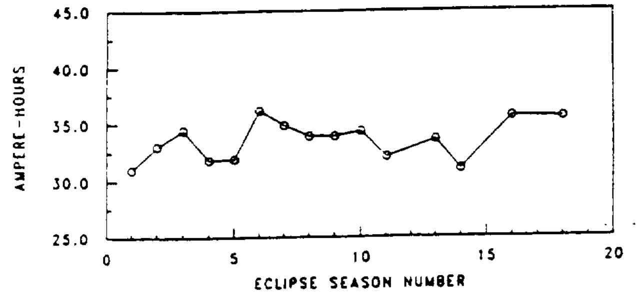


Fig. 2 RECONDITIONING DISCHARGE CAPACITY.

Figure 3 shows the lowest average cell discharge voltage recorded during each of the eclipse seasons. While variations occur due to differences in data recording timing, the trend as a function of time shows only a slight degradation of voltage. The voltage difference from the first to the 18th season shown amounts to 0.0026v/cell, while the orbital time represented is nine years. The test duration in actual time is four years.

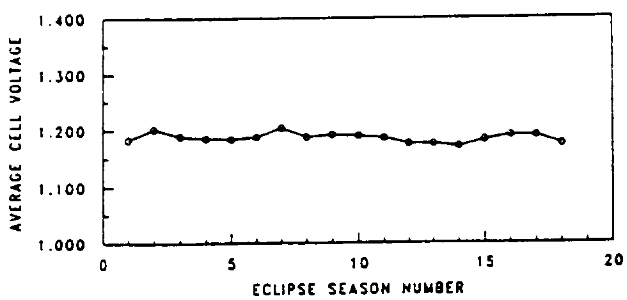


Fig. 3 AVERAGE END-OF-DISCHARGE VOLTAGE at 60% DOD.

Eclipse season data is shown in Figure 4 for season eighteen. The end-of-discharge voltage drops to 1.176v, coinciding with a depth-of-discharge of 60 %. This representative discharge voltage profile shows the downward trend in voltage as daily cycle duration becomes longer until the maximum discharge time of 72 minutes is reached at cycle 22 of the 45 day eclipse season. After five cycles are simulated at 72 minutes, eclipse duration decreases until the 45th cycle concludes the season. Full rate charge periods are adjusted daily to maintain a recharge ratio of 1.15.

A comparison of discharge voltage curves is presented in Figure 5. Shown are longest eclipse days for seasons 1 and 18. Average discharge voltage has decreased only 14mv while the end-of-discharge voltage has changed very little. It is felt that a higher recharge ratio such as 1.20 would correct this voltage change. The higher ratio is well within the design limit of 1.30 at end-of-life (EOL).

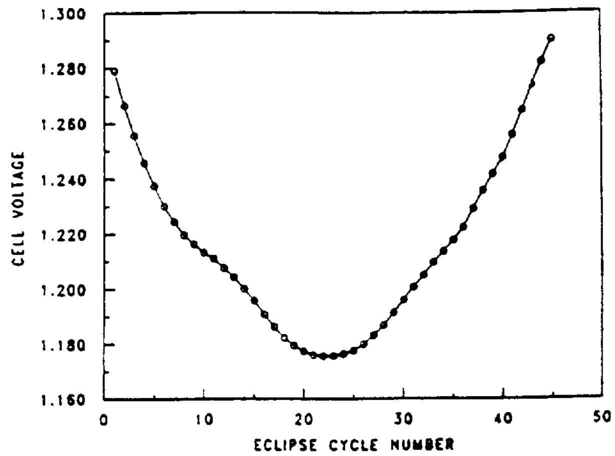


Fig. 4 AVERAGE END-OF-ECLIPSE VOLTAGE at SEASON 18.

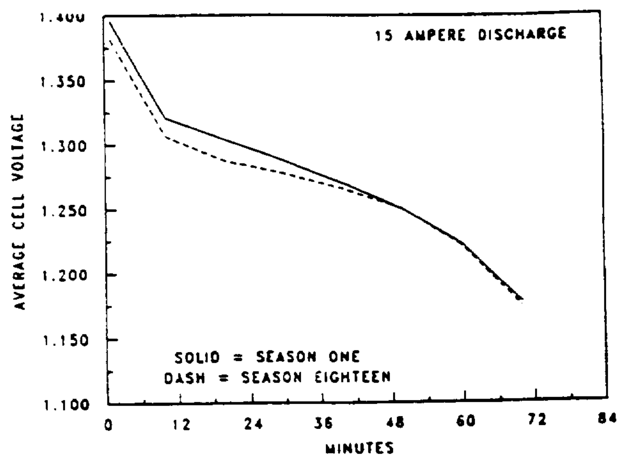


Fig. 5 TYPICAL CELL DISCHARGE VOLTAGE DURING 72 MINUTE ECLIPSE.

Figure 6 presents maximum charge voltages achieved for the longest eclipse day of each of the 18 seasons. The gradual increase for the first four seasons is followed by stable voltages for the remainder of the testing covered. Variations in data points are attributable to data recording timing differences, and not to performance variation. These data points represent the full charge rate end-of-charge voltages; the peak voltage of 1.504v/cell at season 18 is lower than predicted for orbital EOL at seven years or fourteen seasons.

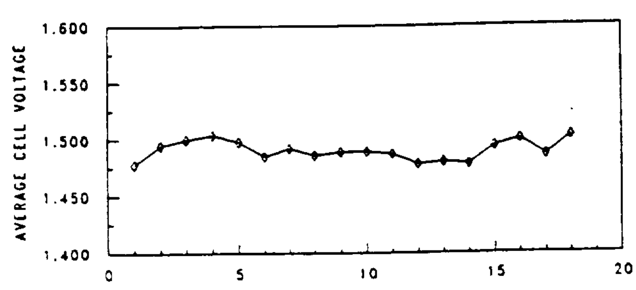


Fig. 6 AVERAGE END-OF-CHARGE VOLTAGE WITH 115% CHARGE RETURN.

SUMMARY

The semi-accelerated life test performed on the INTELSAT-V nickel-hydrogen battery design was initiated prior to the launch of the first such battery system flown on any commercial satellite, flight model 6 of the INTELSAT-V series of communication satellites. The semi-accelerated rate was incorporated so that performance trends could be identified prior to the equivalent point acheived on the spacecraft batteries flying.

The results indicate that there is no significant degradation mode which is out of the ordinary. Battery capacity has remained stable. End-of-discharge voltage and average discharge voltage has changed slightly and with a higher recharge ratio it would likely be constant. End-of-charge voltages have increased only slightly. The performance of the life test battery has exceeded early expectations of end-of-life battery performance. The laboratory data supports the actual flight data observed on six spacecraft flying with this battery system.

The test data supports the design requirement that the battery be qualified to operate at 60% depth-of-discharge for a seven year mission.

REFERENCES

1. "Nickel-Hydrogen Batteries for INTELSAT V," G. van Ommering, C. W. Koehler, and D. C. Briggs, Proceedings of the 15th Intersociety Energy Conversion Engineering Conference, August, 1980, p. 1885.

"THE NI-H_2 BATTERY SYSTEM: A SPACE FLIGHT APPLICATION SUMMARY"

LEE MILLER
EAGLE-PICHER INDUSTRIES, INC. (EPI)

Abstract

It is generally accepted nickel-hydrogen will be the major rechargeable battery system selected for high-reliability, aerospace applications such as spacecraft through at least the remainder of this century. Therefore, it may be of benefit to potential aerospace users and others interested in system reliability aspects if an application summary were offered. For example, it may not be common knowledge there have been 16 satellite launches which have flown the Ni-H_2 battery system. Furthermore, these missions in total have surpassed 20,000,000 battery cell hours of space flight operation. Both of these data would be significantly greater but further launches were delayed as the results of the STS accident.

This paper will summarize the aerospace programs which have flown, are flying and will fly the Ni-H_2 battery systems.

Background

The nickel-hydrogen battery design has been promoted as the most advanced, long life, rechargeable battery technology developed over the last 50 years. Per unit weight this system should offer more than twice the power available from the previously used battery system (nickel-cadmium). In the area of electrical cycle life capacity, a projected 30,000 cycle, 15 year capability (versus 10,000 - 15,000 cycles and 5-7 years for nickel-cadmium) renders a system ability to actually outlast the equipment in which it may be installed. In addition the nickel-hydrogen battery offers a true hermetically sealed design which means it is totally maintenance free and the danger of electrolyte leakage is virtually eliminated.

This design also offers the advantage of not requiring acceptance of new electrochemical technology by the potential user. The Ni-H_2 battery cell simply combines the best features of the nickel-cadmium (Ni-Cd) system (positive electrode) and the hydrogen/oxygen (H_2/O_2) fuel cell system (H_2 electrode). A simple, common gas design evolves which features only established, and both chemically and structurally stable components (thus a high DOD and long cycle life capability), and which can operate over a wide temperature range (-20 degrees to 40 degree C has been demonstrated).

The electrochemical reactions involved are straightforward and are well known within the industry. For the first time a hermetically sealed, rechargeable battery system is available which can sustain high rate overcharge and even overdischarge without short term or long term system degradation. In addition, the reactions are "H_2O" balanced which is very important from an electrolyte management stand point.

By replacing one of the two opposing metal electrodes (conventional internal battery cell design) with hydrogen gas, significant system benefits are achieved. The weight of the replaced metal electrodes are of course eliminated plus overall system performance is enhanced. The potential for metal-to-metal shorting is minimized and the lack of a "wear-out" mechanism for a gas reaction greatly improves system cycle life capability. The nickel-hydrogen battery system has already demonstrated an abuse tolerance (both operational and environmental) far in excess of any competitive battery and this simply translates into superior system reliability.

Because of this inherent reliability, the nickel-hydrogen system has been initially designed and produced for "high rel" aerospace applications. To the extent this technology has been, is now and will be applied in this industry is the subject of this paper.

Space Flight Application Summary

The subject flight programs will be summarized under four (4) categories as follows:

I. Programs Which Have Flown
   These programs are now complete.

II. Programs Which Are Flying
   These programs have satellites now in operation and may have additional launches scheduled.

III. Programs Which Will Fly
   These programs are in the hardware production phase, but no launch has occurred as of this date.

IV. Programs Which Plan to Fly
   These programs are committed to or are seriously considering the application of the Ni-H_2 battery system.

To facilitate a review of this information, the associated data will be presented in a tabular format under the above headings. The program will be identified and pertinent details listed.

Although EPI, in its role as a battery and a battery cell manufacturer, has some general program level knowledge, a few program detail errors may occur. We are obliged to apologize in advance if this is the case.

I. Programs Which Have Flown:

1. USAF "Flight Experiment"

a) Prime Contractor - LMSC
b) Mission - LEO
c) Duration - approximately one (1) year
d) Battery Capacity - 50 Ahr
e) Battery Size - 21 cells
f) Launch Date - 1976

2. US Navy "NTS-2 Satellite"

a) Prime Contractor - TRW/Comsat
b) Mission - High altitude polar, similar to accelerated GEO
c) Duration - approximately eight (8) years
d) Battery Capacity - 35 Ahr
e) Battery Size - Two (2) 7 cell modules connected in series
f) Launch Date - 1976

II. Programs Which Are Flying:

3. "Intelsat V"

a) Prime Contractor - FACC
b) Mission - GEO
c) Duration - Longest, five (5) years now
d) Battery Capacity - 30 Ahr
e) Battery Size - 27 cells
f) Launch Date - 1983 (2), 1984 (1)
1985 (3), 1986 (1)

4. "Spacenet"

a) Prime Contractor - RCA
b) Mission - GEO
c) Duration - Longest, four (4) years now
d) Battery Capacity - 40 Ahr
e) Battery Size - Two (2) 11 cell modules connected in series
f) Launch Date - 1984 (2)

5. "G-Star"

   a) Prime Contractor - RCA
   b) Mission - GEO
   c) Duration - Longest, three (3) years now
   d) Battery Capacity - 30 Ahr
   e) Battery Size - Two (2) 11 cell modules connected in series
   f) Launch Date - 1985 (1), 1986 (1)

6. "American Sat"

   a) Prime Contractor - RCA
   b) Mission - GEO
   c) Duration - Three (3) years now
   d) Battery Capacity - 35 Ahr
   e) Battery Size - Two (2) 11 cell modules connected in series
   f) Launch Date - 1985

7. "Sat Com K"

   a) Prime Contractor - RCA
   b) Mission - GEO
   c) Duration - Longest, three (3) years now
   d) Battery Capacity - 50 Ahr
   e) Battery Size - Two (2) 11 cell modules connected in series
   f) Launch Date - 1985 (1), 1986 (1)

III. Programs Which Will Fly:

8. "Olympus"

   a) Prime Contractor - BAe (UK)
   b) Mission - GEO
   c) Duration - 10 year requirement
   d) Battery Capacity - 35 Ahr
   e) Battery Size - 31 cells
   f) Launch Date - First projected 1989

9. "Intelsat VI"

   a) Prime Contractor - HAC
   b) Mission - GEO
   c) Duration - 10 year requirement
   d) Battery Capacity - 44 Ahr
   e) Battery Size - Two (2) 16 cell modules connected in series
   f) Launch Date - First projected 1989

10. "Military Satellite"

Detailed information on these type applications is classified.

11. "Milstar"

a) Prime Contractor - LMSC
b) Mission - Multiple orbits
c) Duration - 10 year equipment
d) Battery Capacity - 76 Ahr
e) Battery Size - 22 cells
f) Launch Date - First projected 1990

12. "Italsat"

a) Prime Contractor - FACC
b) Mission - GEO
c) Duration - 10 year requirement
d) Battery Capacity - 30 Ahr
e) Battery Size - 27 cells
f) Launch Date - First projected 1989

13. "SCS-1"

a) Prime Contractor - FACC
b) Mission - GEO
c) Duration - 15 year requirement
d) Battery Capacity - 83 Ahr
e) Battery Size - 27 cell
f) Launch Date - First projected 1989

14. "Space Telescope (ST)"

a) Prime Contractor - LMSC
b) Mission - LEO
c) Duration - Five (5) year requirement
d) Battery Capacity - 90 Ahr
e) Battery Size - 23 cells
f) Launch Date - First projected 1990

15. "HBO Satellite"

a) Prime Contractor - RCA
b) Mission - GEO
c) Duration - 10 year requirement
d) Battery Capacity - 50 Ahr
e) Battery Size - Two (2) 11 cell modules connected in series
f) Launch Date - First projected 1989

16. "Anik-E Satellite"

a) Prime Contractor - Spar/RCA
b) Mission - GEO
c) Duration - 12 year requirement
d) Battery Capacity - 50 Ahr
e) Battery Size - Two (2) 11 cell modules connected in series
f) Launch Date - First projected 1989

17. "TV-Sat 2"

a) Prime Contractor - MBB/AEG (Germany)
b) Mission - GEO
c) Duration - 10 year requirement
d) Battery Capacity - 30 Ahr
e) Battery Size - 27 cells
f) Launch Date - First projected 1988

18. "Eutelsat II"

a) Prime Contractor - ASCA (France)
b) Mission - GEO
c) Duration - 10 year requirement
d) Battery Capacity - 65 Ahr
e) Battery Size - 27 cells
f) Launch Date - First Projected 1989

19. "Military Satellite"

Detailed information on these type applications is classified.

20. "Telecom 2"

a) Prime Contractor - Matra (France)
b) Mission - GEO
c) Duration - 10 year requirement
d) Battery Capacity - 78 Ahr
e) Battery Size - 27 cells
f) Launch Date - First projected 1990

V. Programs Which Plan to Fly

21. "Space Station"

a) Prime Contractor - FACC (Power Subsystem)
b) Mission - LEO
c) Duration - 6.5 year requirement
d) Battery Capacity - 81 Ahr
e) Battery Size - 30 cells
f) Launch Date - Mid 1990's

22. "Columbus" (European Space Station)

a) Prime Contractor - AEG (Germany)
b) Mission - LEO
c) Duration - N/A
d) Battery Capacity - N/A
e) Battery Size - N/A
f) Launch Date - Mid 1990's

23. "SAX Satellite"

a) Prime Contractor - FIAR (Italy)
b) Mission - LEO
c) Duration - Four (4) year requirement
d) Battery Capacity - 30 Ahr
e) Battery Size - 29 cells
f) Launch Date - First projected 1990

NOTE: For the remaining applications under this category, we are not certain the prime contractor has been selected as of this date. The proposed detail program information which has been provided to EPI varies between prime contractors. It would not be appropriate to publish this information and only the program name and mission will be identified.

24. "Olympus" Follow On
b) Mission - GEO

25. "Italsat" Follow On
b) Mission - GEO

26. "UHF" Follow On
b) Mission - LEO

27. "X-Ray Telescope"
b) Mission - LEO

28. "Intelsat VII"
b) Mission - GEO

29. "Aussat B"
b) Mission - GEO

30. "GPS Block IIR"
b) Mission - GEO

31. "Inmarsat II"
b) Mission - LEO

32. "Super Program"
    b) Mission - Multiple orbits

33. "Military Satellites"

    At this time a total of six (6) programs are qualified for classification under this category.

Conclusion

This limited review has identified 38 programs which have, are or will likely constitute the applications base for this battery technology. It is hoped this summary will provide a useful reference for potential users and others who may be interested in the extent of the application of the nickel-hydrogen battery system.

"NiH_2 LEO LIFE TEST AT NWSC (CRANE): CELL CHARACTERIZATION RESULTS"

TONY FELTS

The next speaker was Tony Felts who described the "NiH_2 LEO Life Test at NWSC (Crane): Cell Characterization Results." The major objectives of the work (Felts [Figure 3]) are to:

Demonstrate NiH_2 performance in LEO

Develop a statistically significant data base

Provide uniform, comparable data from various vendors

The goals are to develop minimum cycle lives as shown in the chart and to achieve a minimum reliability of 90 percent at an 80 percent confidence limit.

The approach is, (Felts [Figure 4]), to test cells under LEO and mid-altitude orbit (MAO) regimes.

Acceptance testing was performed on both Gates and Yardney cells (Felts [Figure 8]). The best capacities occur at 0 degree C for cells from both vendors. Cell characterization tests, (Felts [Figure 10]), were performed for five Gates and five Yardney cells (both types having 3.5" diameters). It was found that efficiencies decrease as discharge rates increase. The Yardney cells were more sensitive to temperatures. (Felts [Figures 11 through 16]).

It was found, (Felts [Figure 17]), that cell impedance dominates efficiency. Also the charge rate has a complex effect on efficiency.

The objectives of the life test charging algorithm study, (Felts [Figure 19]), were to minimize the following parameters:

Decrease in the EOD voltage
Increase in the EOC parameter recharge fraction.

At this time three Yardney packs and one Gates pack are undergoing life tests Felts [Figure 20] 3.5" cells from EPI and Hughes will be life cycle tested by the second quarter of FY88. 4.5" cells from all vendors should be in test by the end of FY88 (Felts [Figure 23]).

Q. Mackowski (McDD): What are the specific charge rates?

A. Charge rates have been 50, 25, 12.5, and 5 amps. They vary widely and may differ for each cell pack.

Q. Thaller (LeRC): At 60 percent DOD shouldn't the recharge ratio efficiency be inversely proportional to DOD?

A. Didn't find it in the curves.

Q. Badcock (Aerospace): The core temperatures in the cell are so high that they raise the currents.

NICKEL HYDROGEN LOW EARTH ORBIT LIFE TEST AT NWSC/CRANE: CELL CHARACTERIZATION RESULTS

A. B. FELTS, R. L. HAAG, AND S. HALL
NAVAL WEAPONS SUPPORT CENTER
CRANE, IN 47522

C. C. BADCOCK AND S. W. DONLEY
THE AEROSPACE CORPORATION
EL SEGUNDO, CA 90245

FOR PRESENTATON AT THE

1987 NASA/GFSC BATTERY WORKSHOP

GREENBELT, MD

4 - 5 NOVEMBER 1987

FIGURE 1. FELTS

NiH$_2$ LEO LIFE TEST

1. INTRODUCTION
2. ACCEPTANCE TEST RESULTS
3. CHARACTERIZATION TEST RESULTS
4. LIFE TEST STATUS
5. SUMMARY

FIGURE 2. FELTS

NiH_2 LEO LIFE TEST

- * OBJECTIVES
  - * DEMONSTRATE NiH_2 PERFORMANCE IN LEO
    - * SUPPORT MID-ALTITUDE ORBIT OPERATION
    - * RELATE LARGE DIAMETER CELLS TO DATA BASE
  - * DEVELOP A STATISTICALLY SIGNIFICANT DATA BASE
    - * PROJECT BATTERY RELIABILITIES
    - * SUPPORT OTHER TESTING DATA
  - * PROVIDE A UNIFORM, COMPARABLE DATA
    - * INCORPORATE OTHER DATA BASES
    - * DIRECT COMPARISONS OF MANUFACTURERS' CELLS
- * GOALS
  - * DEMONSTRATE A MINIMUM CYCLE LIFE
    - * 30,000 CYCLES AT 40% DOD
    - * 20,000 CYCLES AT 60% DOD
    - * 5000 CYCLES AT 80% DOD (MAO ORBIT)
  - * ACHIEVE A MINIMUM RELIABILITY
    - * 90% RELIABILITY AT AN 80% CONFIDENCE LIMIT

FIGURE 3. FELTS

NiH_2 LEO LIFE TEST
ORGANIZATION AND APPROACH

- * ORGANIZATION
  - * PROGRAM MANAGEMENT BY AFSTC
  - * NWSC/CRANE TO PERFORM ACCEPTANCE, CHARACTERIZATION, AND LIFE TESTING
    - * DOD NATIONAL TEST FACILITY FOR BATTERIES AND CELLS
  - * AEROSPACE TO PROVIDE TECHNICAL SUPPORT
    - * PREPARE DOCUMENTATION AND ASSIST IN REPORTING RESULTS
    - * PERFORM SPECIALIZED TESTING
  - * AFWAL/POOC TO SUPPORT PROGRAM
    - * PROVIDE PREVIOUSLY PURCHASED CELLS AND PURCHASE SERVICES FOR FIRST CELLS PURCHASED (FY86)
- * APPROACH
  - * TEST CELLS UNDER LEO AND MAO REGIMES (MAJORITY IN LEO)
    - * LIMIT VARIABLES TO INCREASE STATISTICAL SIGNIFICANCE
    - * TEST UNDER MOST BENIGN, ACHIEVABLE CONDITIONS
    - * TEST CELLS FROM ALL VIABLE US MANUFACTURERS
    - * TEST 3.5 AND 4.5 INCH DIAMETER CELLS

FIGURE 4. FELTS

NiH_2 LEO LIFE TEST
TEST PARAMETERS

* TEST ~80% OF THE CELLS UNDER LEO CONDITIONS
    * 16 CYCLES /DAY: 30 M DISCHARGE/60 M CHARGE
    * MAO TESTING USING A 6 HOUR CYCLE
    * DEPTH OF DISCHARGE BASED ON ACTUAL PACK MINIMUM CAPACITY
        * LEO
            * 25% (CORRELATION WITH NICD ONLY)
            * 40% IS THE CONSERVATIVE GOAL
            * 60% IS THE DESIRED GOAL
        * MAO
            * 80% WILL PERMIT BOL DESIGNS AT 70+%
    * TEMPERATURE
        * LEO TESTING AT 10°C AND -5°C (±4°C)
        * MAO TESTING AT 10°C ONLY
    * CHARGE CONTROL MINIMIZES QUANTITY OF EXCESS CHARGE AND RATE DURING OVERCHARGE (ALGORITHM DEVELOPED)

FIGURE 5. FELTS

NiH_2 LEO LIFE TEST

SCHEDULE

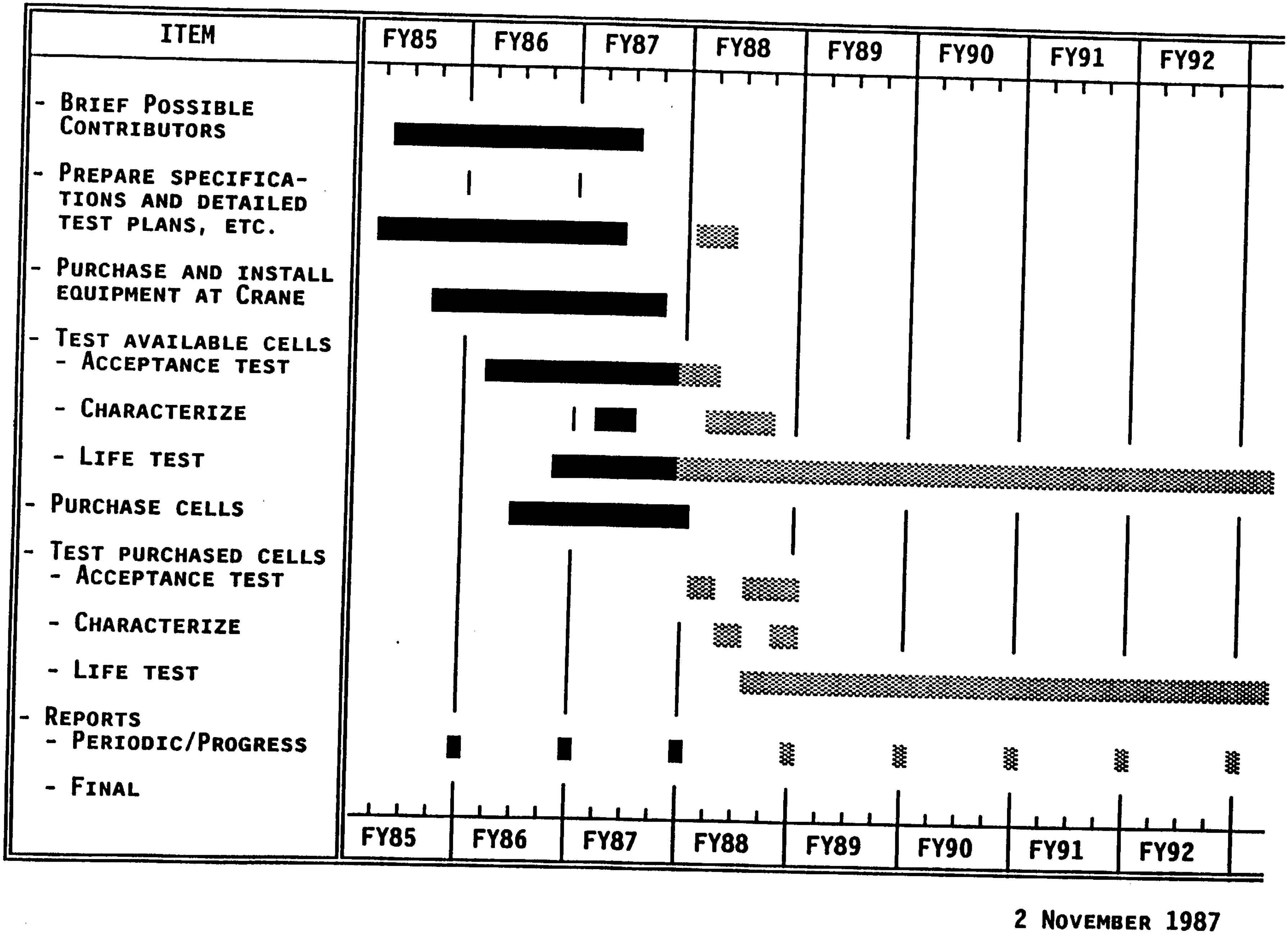


FIGURE 6. FELTS

NiH_2 LEO LIFE TEST

1. INTRODUCTION
2. **ACCEPTANCE TEST RESULTS**
3. CHARACTERIZATION TEST RESULTS
4. LIFE TEST STATUS
5. SUMMARY

FIGURE 7. FELTS

CAPACITIES FROM ACCEPTANCE TESTING

CONDITIONS	-5°C	0°C	10°C	20°C	30°C
CHARGE	25A/2H 5A/6H	25A/2H 5A/64H	25A/2H 5A/6H	25A/2H 5A/8H	25A/2H 5A/8H
DISCHARGE	---------- 50A TO 1.0 V ----------				
MEAN CAPACITY (AH)					
GATES (15 CELLS)	67.43	73.82	70.87	66.13	57.85
STD. DEVIATION	1.34	0.84	0.38	0.91	0.77
YARDNEY (31 CELLS)	56.00	61.16	56.12	52.45	47.37
STD. DEVIATION	3.31	4.89	2.65	2.74	2.64

* 20% OF THE CELLS WERE SUBJECTED TO RANDOM VIBRATION TESTING

FIGURE 8. FELTS

NiH_2 LEO LIFE TEST

1. INTRODUCTION
2. ACCEPTANCE TEST RESULTS
3. CHARACTERIZATION TEST RESULTS
4. LIFE TEST STATUS
5. SUMMARY

FIGURE 9. FELTS

CELL CHARACTERIZATION TESTING

- o **<u>OBJECTIVE:</u>** TO DETERMINE EFFICIENCY AND OPERATING CHARACTERISTICS FOR NiH_2 CELLS

- o **<u>OUTLINE OF TESTING:</u>** CELL EFFICIENCIES ARE FOUND BY VARYING EACH OF THE FOLLOWING PARAMETERS IN TURN:

  -CHARGE RATE (NOMINAL): C, C/2, C/4, C/10

  -DISCHARGE RATE (NOMINAL): 2C, C, C/2

  -TEMPERATURE (DEG. C): -5, 10, 20, 30

  -STATE-OF-CHARGE (AMPERE-HOUR INPUT)

- o **<u>DATA PRESENTED HERE:</u>**

  -5 GATES CELLS (3.5 IN. DIAM.)

  -5 YARDNEY CELLS (3.5 IN. DIAM.)

FIGURE 10. FELTS

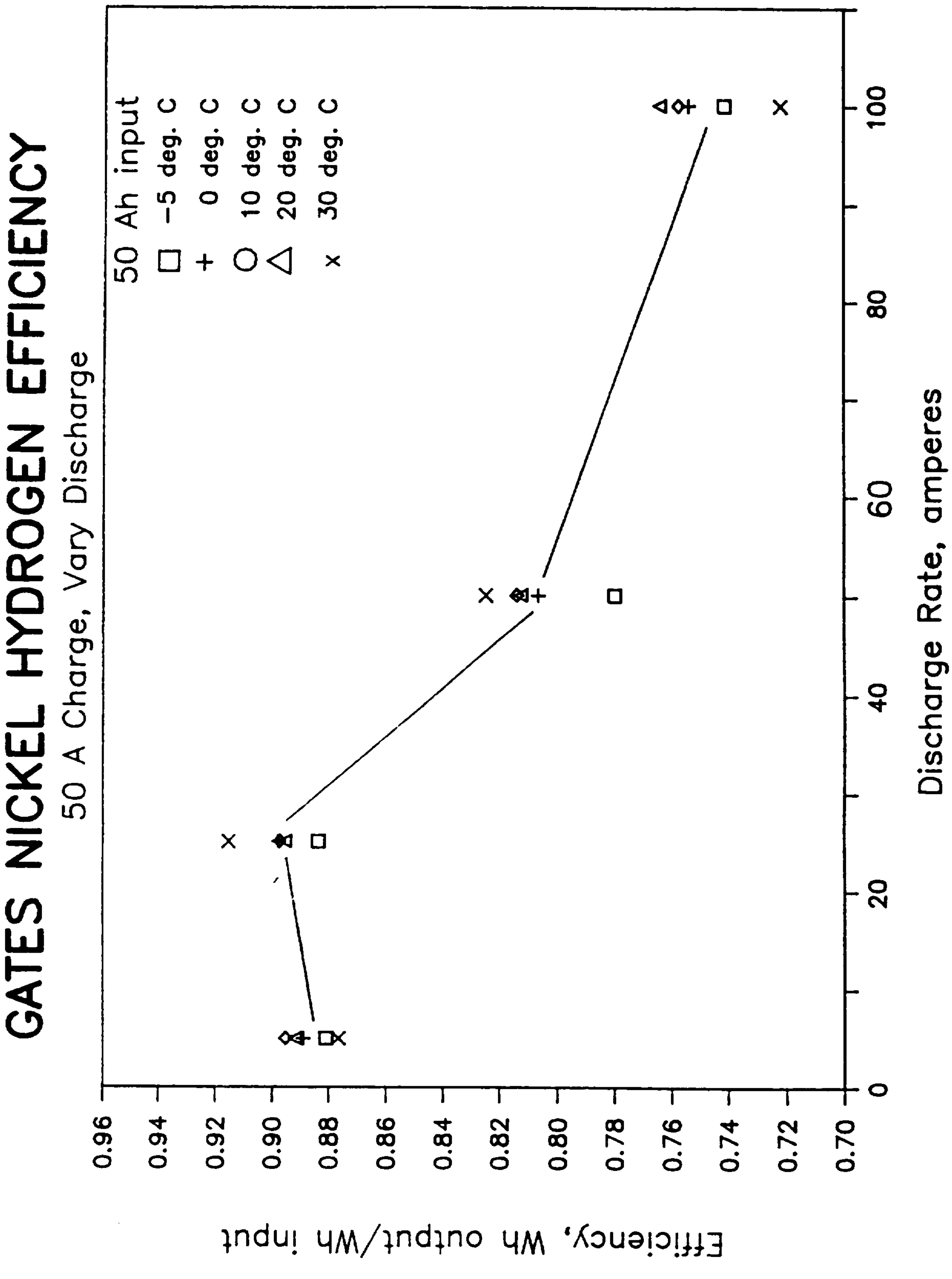


FIGURE 11. GREEN

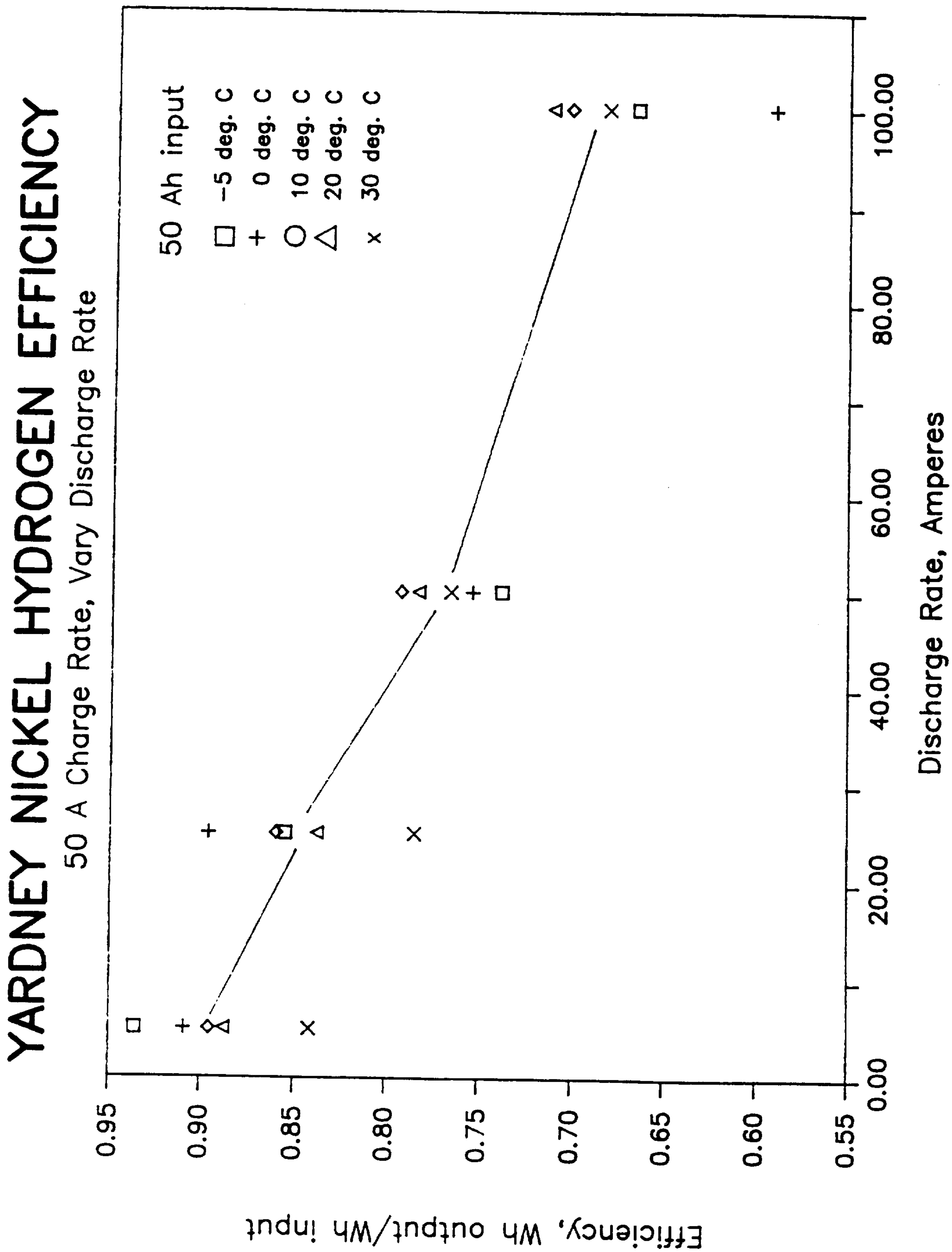


FIGURE 12. FELTS

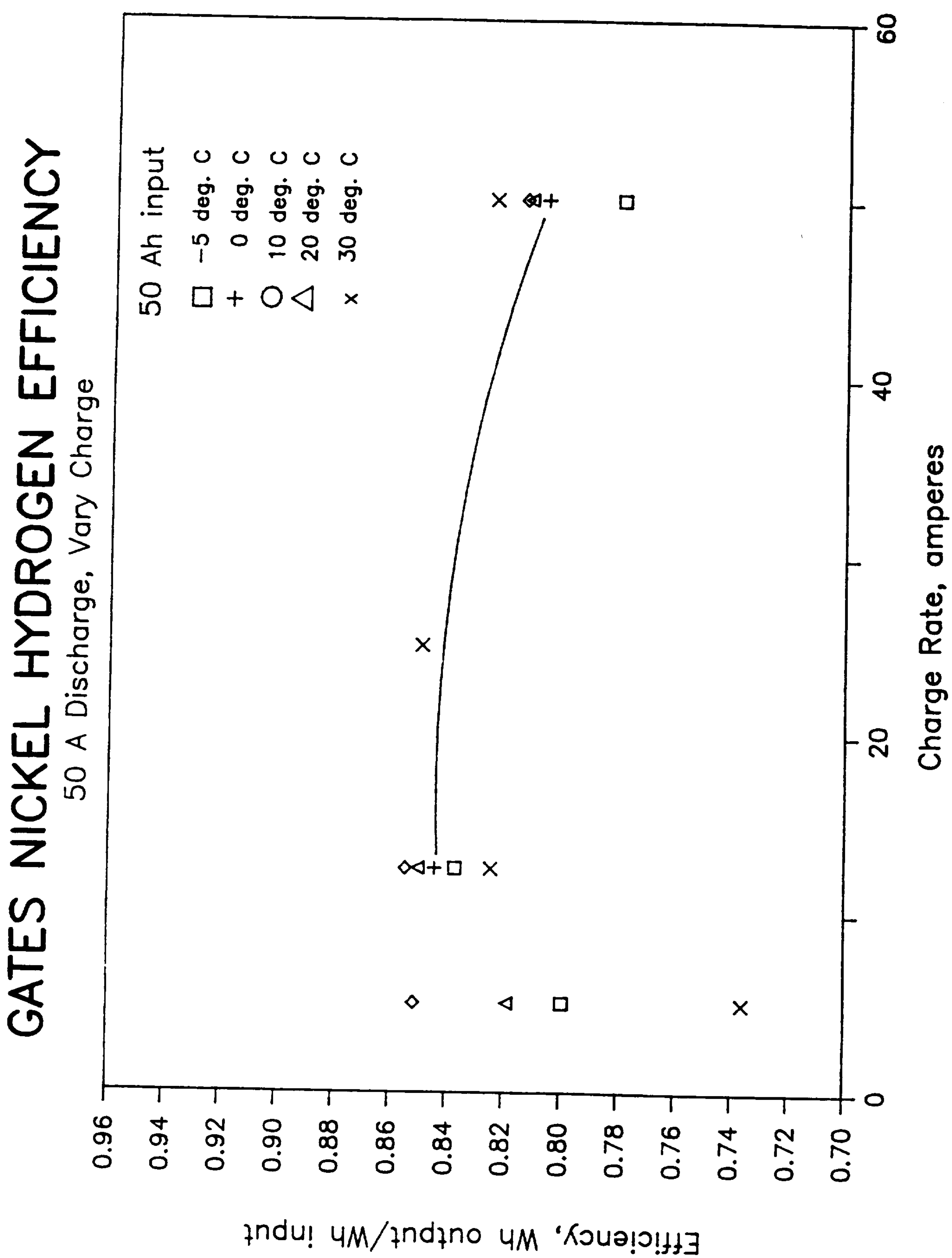


FIGURE 13. FELTS

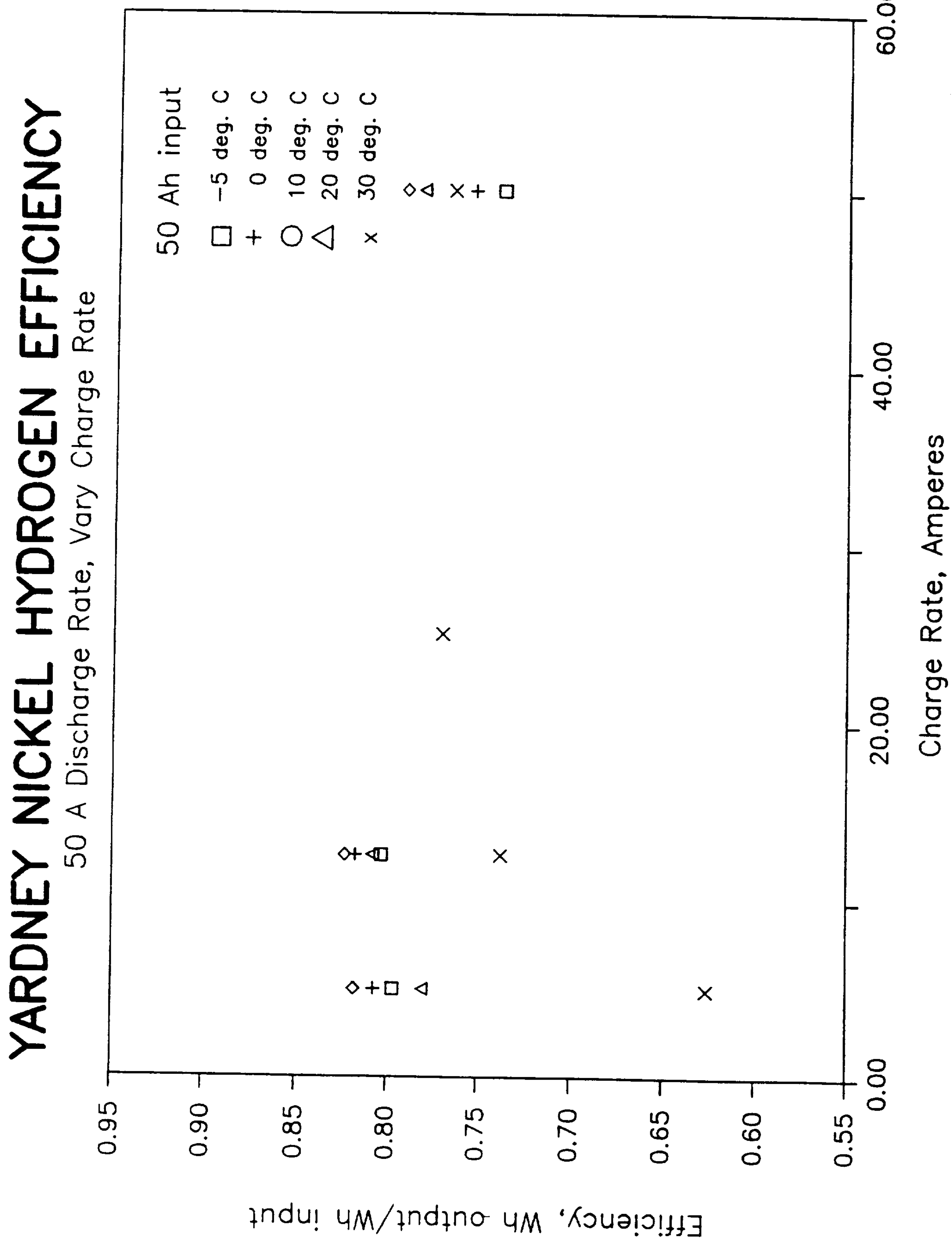


FIGURE 14. FELTS

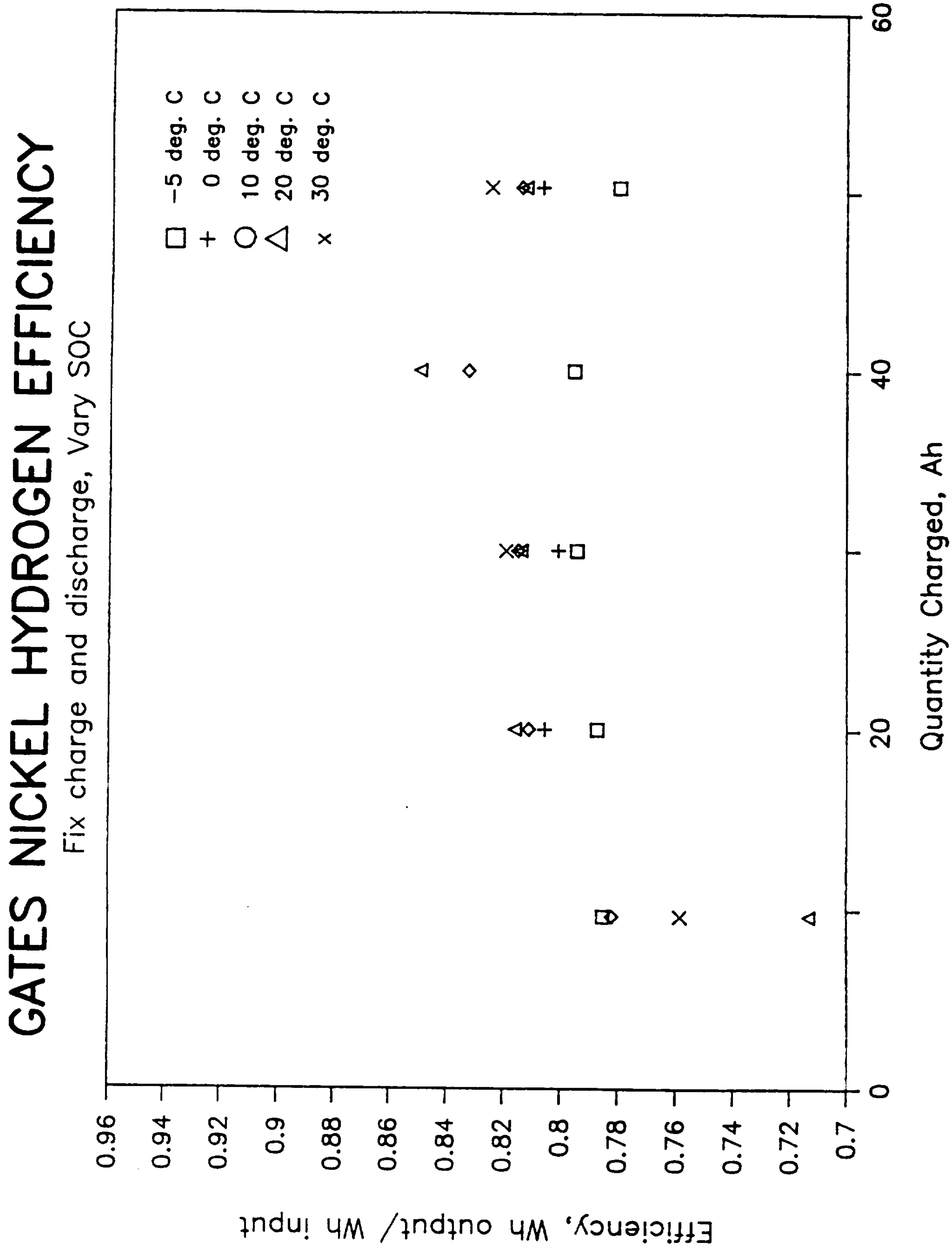


FIGURE 15. FELTS

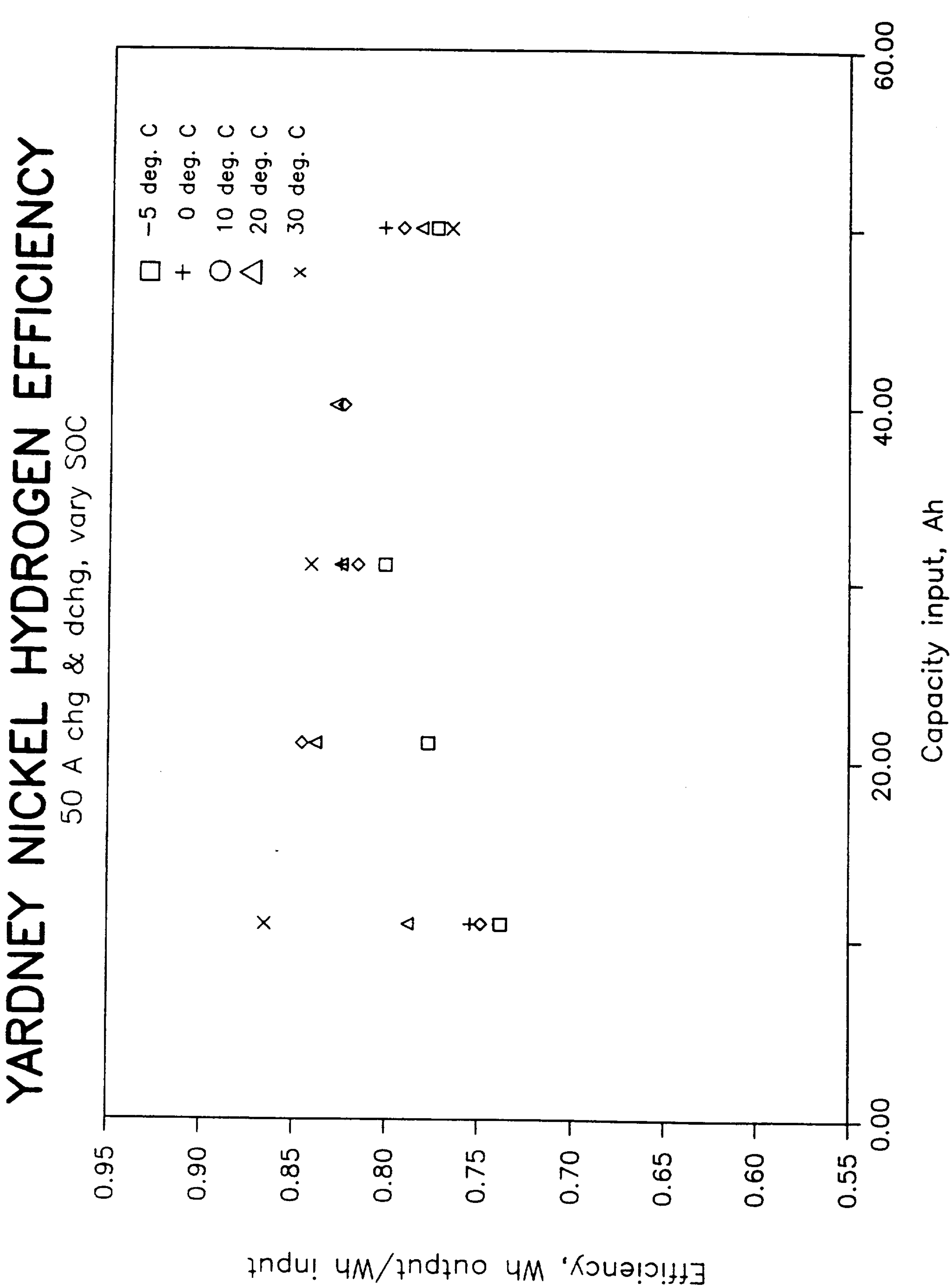


FIGURE 16. FELTS

NiH_2 CHARACTERIZATION SUMMARY
-GATES AND YARDNEY CELLS-

- EFFICIENCY DEPENDENCE ON DISCHARGE RATE IS DOMINATED BY THE CELL IMPEDANCE
- EFFECTS OF CHARGE RATE ON EFFICIENCY MORE COMPLEX
  - EVIDENCE OF EFFECTS OF COULOMBIC EFFICIENCY AND IMPEDANCE
- YARDNEY AND GATES CELLS SIMILAR
  - HIGHER CAPACITY OF GATES CELLS IS REFLECTED IN HIGHER EFFICIENCIES AT 50 AH AND LOWER CHARGE INPUTS (QUANTITIES USED IN EFFICENCY TESTS)

FIGURE 17. FELTS

NiH_2 LEO LIFE TEST

1. INTRODUCTION
2. ACCEPTANCE TEST RESULTS
3. CHARACTERIZATION TEST RESULTS
4. LIFE TEST STATUS
5. SUMMARY

FIGURE 18. FELTS

NiH_2 LEO LIFE TEST
-CHARGING ALGORITHM-

* OBJECTIVES IN LIFE CYCLING:
    * MINIMIZE THE FOLLOWING PARAMETERS
        * DECREASE IN THE END OF DISCHARGE VOLTAGE
        * INCREASE IN END OF CHARGE PARAMETER
        * RECHARGE FRACTION
* PRESENT METHOD:

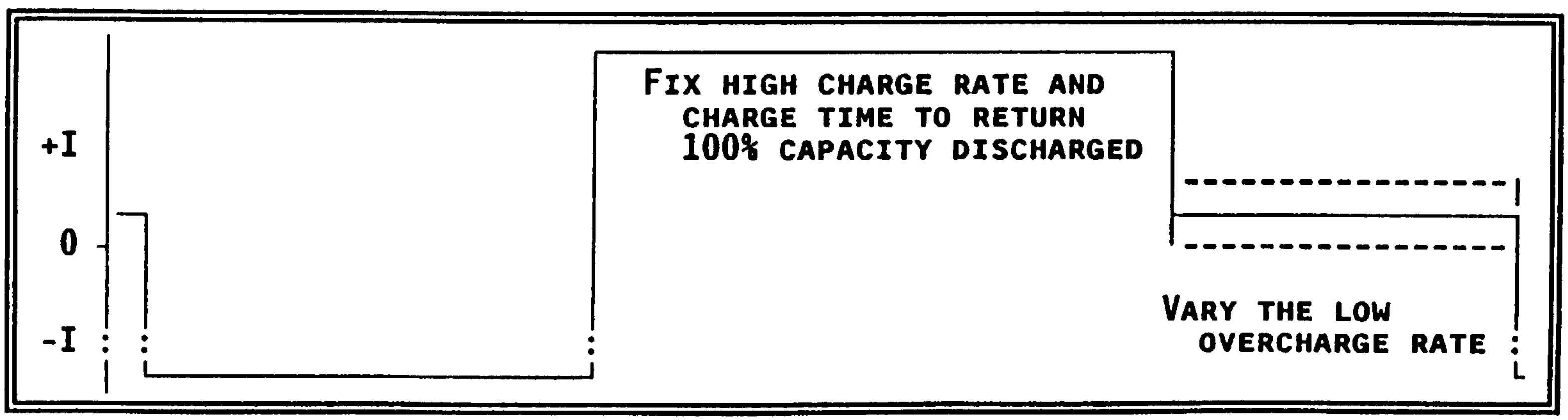


FIGURE 19. FELTS

3.5 INCH NICKEL-HYDROGEN CELL LIFE TEST PACKS STATUS AS OF 10/29/87

PACK	TEMP (C)	#CELLS	%DOD	CYCLE	% RCHG
YARDNEY #1	10	10	40	3603	101.4
YARDNEY #2	-5	10	40	1403	102.5
YARDNEY #3	10	10	60	837	105.6
GATES #1	10	10	60	699	104.4

FIGURE 20. FELTS

NiH_2 LEO LIFE TEST

1. INTRODUCTION
2. ACCEPTANCE TEST RESULTS
3. CHARACTERIZATION TEST RESULTS
4. LIFE TEST STATUS
5. SUMMARY

FIGURE 21. FELTS

NiH_2 LEO LIFE TEST
CELL STATUS

MANUFACTURER	SIZE/CAPACITY	QUANTITY	STATUS
YARDNEY	3.5"/50	31 (ZA)	IN TEST
	3.5"/50	17 (ZA)	DUE 5/88
	4.5"/110	10	DUE 5/88
EAGLE-PICHER (JOP)	3.5"/50	24 (A)	PRE-ATP CYCLING
		33 (Z)	PRE-ATP CYCLING
		15	DUE 7/88
EAGLE-PICHER (CS)	4.5"/100	8 (Z)	ATP, 1/88
	4.5"/130	10 (Z)	DUE 4/88
GEN. ELECTRIC BBD	3.5"/50	15 (Z)	IN TEST
	3.5"/50	15 (Z)	DUE 1/88
	3.5"/50	17 (Z)	DUE 4/88
	4.5"/100	8 (Z)	ATP, 1/88
	4.5"/130	10 (Z)	DUE 4/88
HUGHES AIRCRAFT	3.5"/50	30 (Z)	ATP, 12/87
	4.5"/100	5 (Z)	ATP, 1/88

2 Nov 1987

SUMMARY

- LIFE TEST PROGRAM IN PROGRESS TO PROVIDE REQUIRED DATA
  - -LONG TERM TEST TO ESTABLISH LIFE
  - -COORDINATE WITH OTHER LIFE TEST PROGRAMS
    - -USE ALL DATA TO COMPLETE DATA BASE
- 3.5 IN. DIAM. CELLS FROM TWO VENDORS HAVE BEEN ACCEPTANCE, ENVIRONMENTAL, AND CHARACTERIZATION TESTED AND ARE NOW IN LIFE TEST
- 3.5 IN. DIAM. CELLS FROM EPI AND HAC WILL COMMENCE LIFE CYCLING SECOND QUARTER FY88
- 4.5 IN. DIAM. CELLS FROM ALL VENDORS WILL ENTER TEST IN FY88

FIGURE 23. FELTS

"LEO TESTING OF NiH_2 CELLS AT MARTIN-MARIETTA"

KEN FUHR

Ken Fuhr (Martin-Marietta) gave a presentation entitled "LEO Testing of NiH_2 Cells at Martin-Marietta: A Status Report."

The objective of the work, (Fuhr [Figure 2]), is to develop a data base for low earth orbit use of nickel-hydrogen cells and batteries. For every cell that comes in, there is an initial receiving and inspection test (Fuhr [Figure 3]) As of 1 November 1987 the oldest cells have been tested through 8718 cycles. A reconditioning cycle, (Fuhr [Figures 12 and 13]), is performed when a cell fails. Failure means that the cell cannot maintain one volt at EOD.

Looking at the cell failure chart, (Fuhr [Figure 14]), all but cell 14 are at 60 percent DOD. Apparently cell 14 had a hydrogen leak. The manufacturer repaired it but it failed again. Seventy-nine percent of the failures were at 10 degrees C.

The approach is to life-cycle test both the 3.5" 50 amp-hour and the 4.5" 100 amp-hour NiH_2 cells and eventually get into building a NiH_2 battery.

The maximum temperature rise was about 2 to 3 degrees C during the cell cycling.

Q. __________: Describe the charge regime.

A. There was constant current charging.

Q. George (NASA/MSFC): In the earlier viewgraphs you described the capacity tests. The C/2 charge rate for 16 hours was shown. Was that used for the capacity tests?

A. C/10 for 16 hours is used for capacity tests (there was an error on the chart) performed every 1,000 cycles.

Q. George (NASA/MSFC) On other viewgraphs you say that you do C/10 for 16 hours. Why the difference?

A. The other slides should have read C/10 as well.

NICKEL-HYDROGEN LOW EARTH ORBIT

TESTING AT MARTIN MARIETTA:

A STATUS REPORT

FIGURE 1. FUHR

MARTIN MARIETTA

NICKEL-HYDROGEN LOW EARTH ORBIT TEST PROGRAM

OBJECTIVE

DEVELOP A DATA BASE FOR LOW EARTH ORBIT USE OF NICKEL-HYDROGEN CELLS AND BATTERIES.

APPROACH

LIFE CYCLE LEO TESTING OF BOTH 3.5 INCH, 50 AMPERE-HOUR AND 4.5 INCH, 100 AMPERE- HOUR CELLS WITH VARIOUS DESIGNS FROM ALL NICKEL- HYDROGEN MANUFACTURERS.

FIGURE 2. FUHR

MARTIN MARIETTA

0623-1

INITIAL RECEIVING AND INSPECTION TEST

C/10 CHARGE FOR 16 HOURS

1 HOUR OPEN CIRCUIT STAND

C/2 DISCHARGE TO 0.5 VOLT PER CELL

REPEAT 5 CYCLES

DISCHARGE TO 1.0 VOLT (CAPACITY MEASUREMENT)

FIGURE 3. FUHR

MARTIN MARIETTA

NICKEL-HYDROGEN LEO TEST MATRIX

	40 % DOD	60 % DOD
10°C	16 EP CELLS 16 GE CELLS 6 YARDNEY 4 EP COMSAT	8 EP CELLS 8 GE CELLS
20°C	8 EP CELLS 8 GE CELLS	4 EP CELLS 4 GE CELLS

FIGURE 4. FUHR

MARTIN MARIETTA

100 AMP-HOUR TEST PLAN

# OF CELLS	VENDOR	CELL DESIGN
8	EAGLE PICHER (JOPLIN)	AIR FORCE/COMSAT HYBRID
5	GENERAL ELECTRIC	AIR FORCE
4	YARDNEY	MANTECH
4	EAGLE PICHER (COLO. SPRINGS)	AIR FORCE/HAC

FIGURE 5. FUHR

MARTIN MARIETTA

NICKEL-HYDROGEN LEO TEST MATRIX
4.5 INCH, 100 AMPERE-HOUR

40 % DOD

10°C

8 EAGLE-PICHER (JOPLIN) - ON TEST
5 GATES (GE) - ON TEST
4 YARDNEY ON TEST
4 EAGLE-PICHER (COLORADO SPRINGS) - TO BE DELIVERED NOVEMBER 9, 1987

FIGURE 6. FUHR

MARTIN MARIETTA

LEO TEST STATUS AS OF 1 NOV. 1987

TEST GROUP			TEST STATUS		
VENDOR	TEST TEMP (°C)	# CELLS	DOD (%)	LEO CYCLES COMPLETED	RECHARGE FRACTION
EP	10	16	40	7840	1.058
EP	10	5	60	8536	1.083
EP	20	8	40	8079	1.104
EP	20	4	60	5304	1.130
GE	10	16	40	6656	1.044
GE	10	4	60	5704	1.085
GE	20	7	40	7118	1.072
GE	20	4	60	7380	1.094
YARDNEY	10	6	40	8521	1.055
COMSAT	10	4	40	8718	1.070
GE 4.5	10	5	40	2856	1.050
EP 4.5	10	7	40	3475	1.059
YARDNEY 4.5	10	4	40	1469	1.051

FIGURE 7. FUHR

MARTIN MARIETTA

CAPACITY TEST

PERFORMED EVERY 1000 CYCLES

- DISCHARGE AT C/2 RATE TO 1.0 VOLT
- CHARGE AT C/10 RATE FOR 16 HOURS
- DISCHARGE AT C/2 RATE TO 1.0 VOLT AND RECORD CAPACITY
- CHARGE AT C/10 RATE FOR 16 HOURS AND RETURN TO LEO CYCLING

FIGURE 8. FUHR

MARTIN MARIETTA

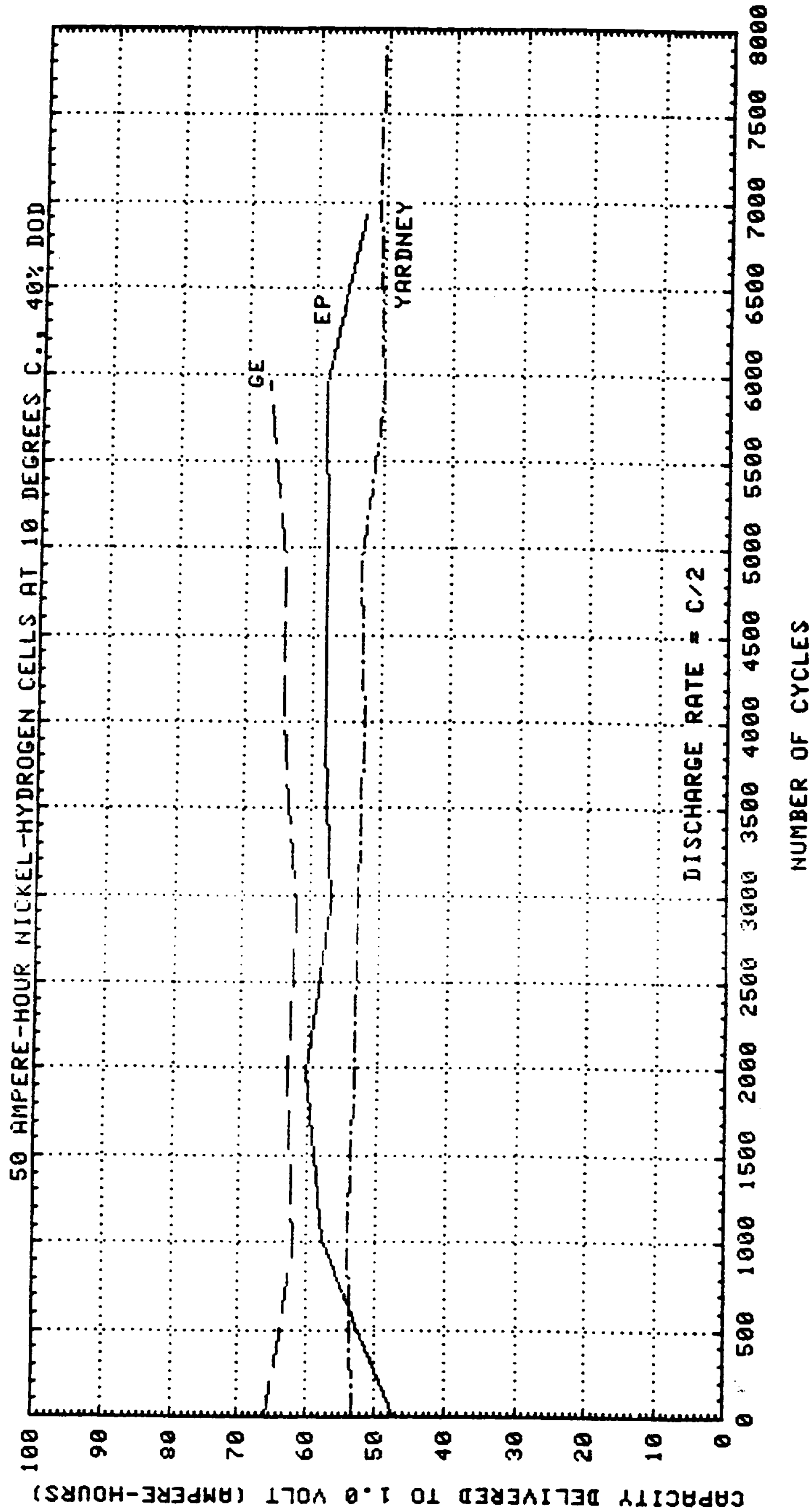


FIGURE 9. FUHR

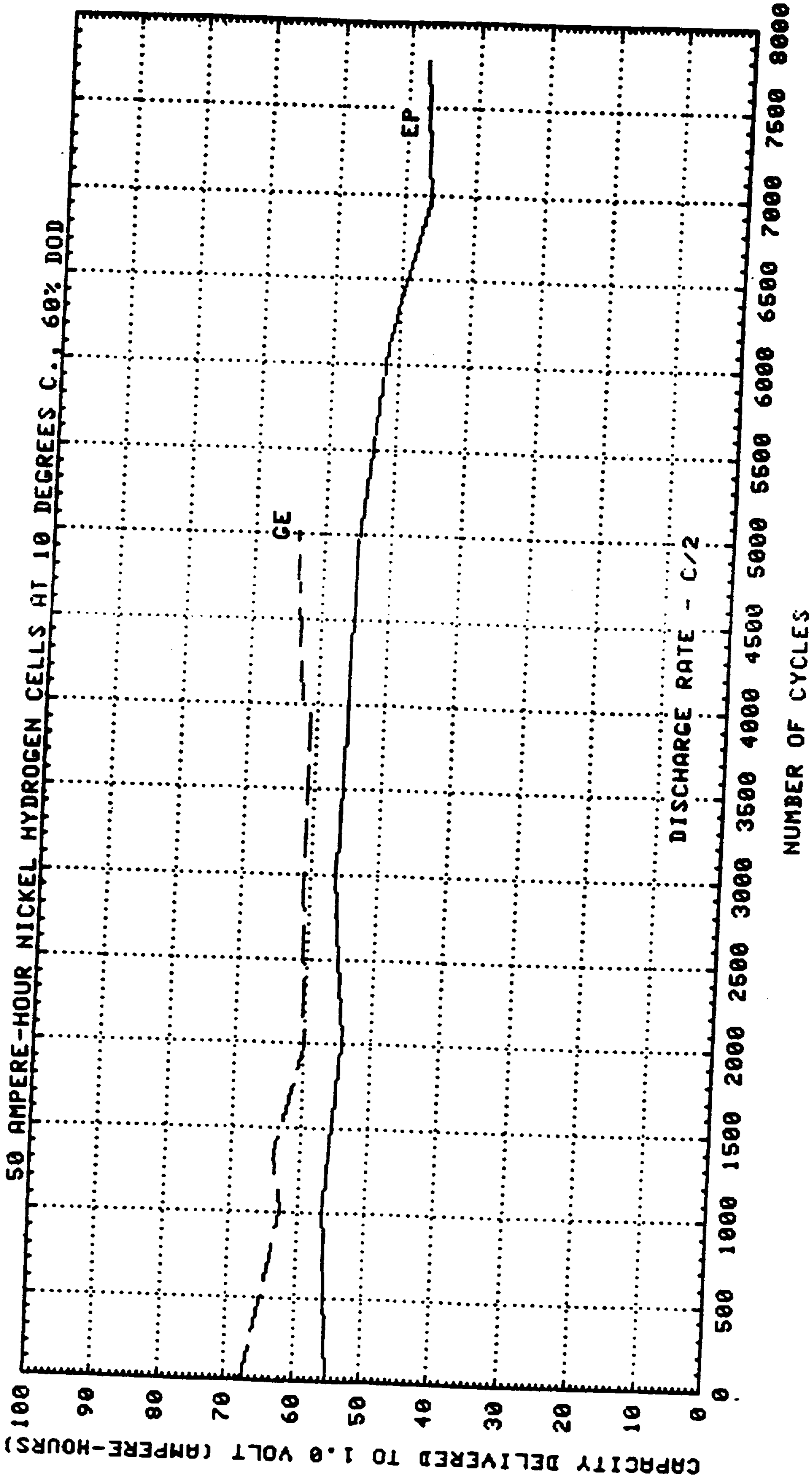


FIGURE 10. FUHR

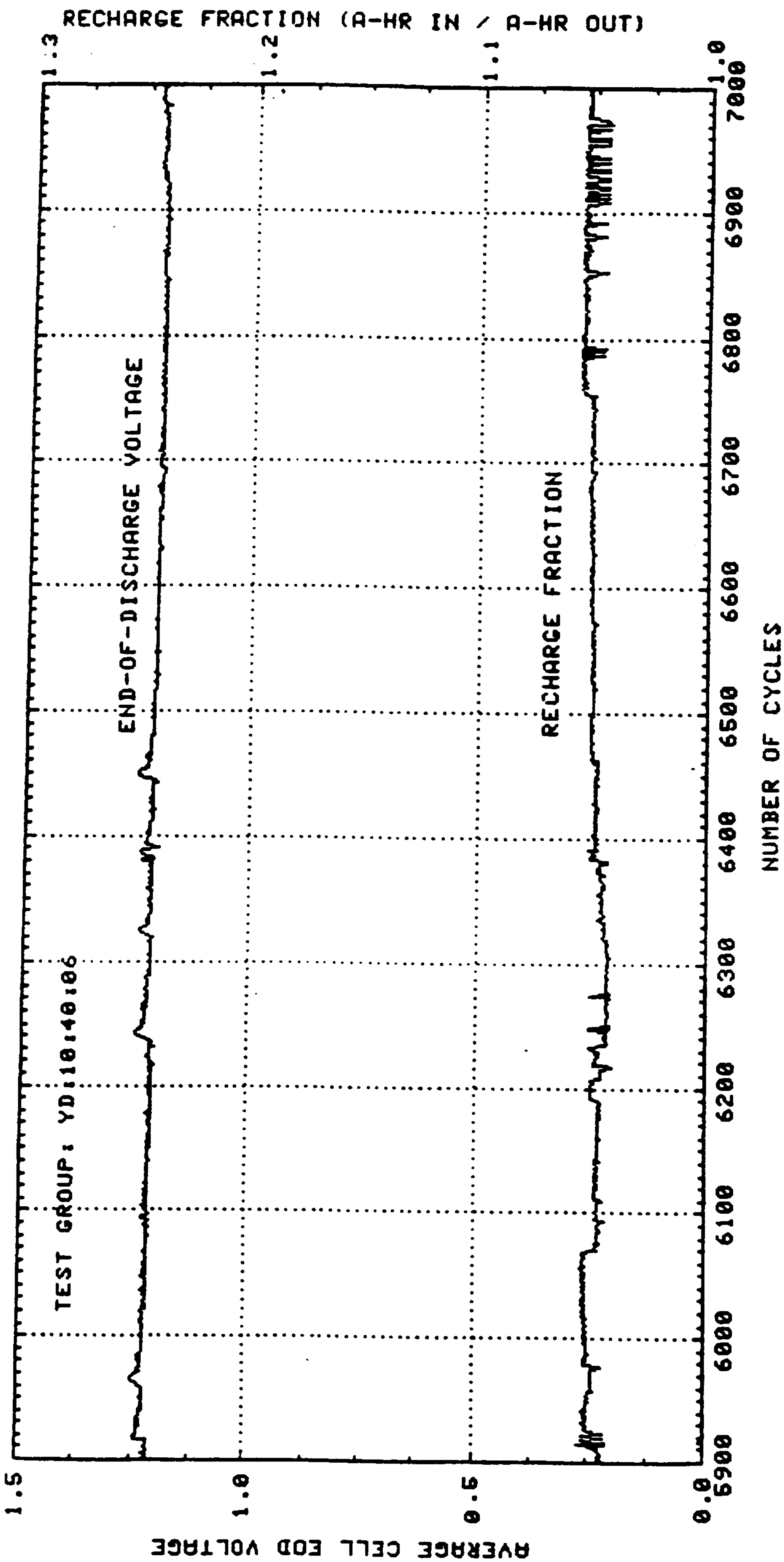


FIGURE 11. FUHR

RECONDITIONING CYCLE

PERFORMED WHEN EOD VOLTAGE REACHES 1.0 VOLT

- TO RECONDITION CELLS
- TO OBSERVE 72 HOUR SELF DISCHARGE RATE

FIGURE 12. FUHR

MARTIN MARIETTA

RECONDITIONING CYCLE

- REMOVE FROM TEST AND DISCHARGE TO 0.0 VOLTS WITH A 1 OHM RESISTOR
- CHARGE AT A C/10 RATE FOR 16 HOURS
- DISCHARGE AT C/2 RATE TO 1.0 VOLT AND RECORD CAPACITY
- DISCHARGE TO 0.0 VOLTS WITH A 1 OHM RESISTOR
- CHARGE AT A C/10 RATE FOR 16 HOURS
- ALLOW CELLS TO STAND ON OPEN CIRCUIT FOR 72 HOURS
- DISCHARGE AT A C/2 RATE TO 1.0 VOLT AND RECORD CAPACITY
- CHARGE AT A C/10 RATE FOR 16 HOURS AND RETURN TO LEO CYCLING

FIGURE 13. FUHR

MARTIN MARIETTA

CELL FAILURES

TEST GROUP	CELL CAPACITY	CYCLE IN WHICH FAILURE OCCURRED
1) 10°C, 60% DOD	50 AH	511
2) 10°C, 60% DOD	50 AH	2291
3) 10°C, 60% DOD	50 AH	4032
4) 10°C, 60% DOD	50 AH	4032
5) 20°C, 60% DOD	50 AH	5304
6) 20°C, 60% DOD	50 AH	5304
7) 10°C, 60% DOD	50 AH	6951
8) 10°C, 60% DOD	50 AH	7326
9) 10°C, 60% DOD	50 AH	7496
10) 20°C, 60% DOD	50 AH	7058
11) 10°C, 60% DOD	50 AH	7904
12) 10°C, 60% DOD	50 AH	8090
13) 10°C. 60% DOD	50 AH	8282
14) 10°C, 40% DOD	100 AH	711 (1956)

FIGURE 14. FUHR

MARTIN MARIETTA

"PARAMETRICS OF NIH_2 CELL DESIGN"

ARNOLD HALL

Arnold Hall (Whittaker-Yardney) gave the next two papers. The first paper was "Parametrics of NiH_2 Cell Design."

Hall is concerned with determining the dominant trade-off parameters to be used in designing NiH_2 individual pressure vessel (IPV) type cells. These are the parameters to use in comparative evaluations.

There is an optimum cell weight driven by the pV = nRT gas law. Without tabs the basic weight is proportional to pressure (Hall [Figure 2]). The practical design range is limited to 700 to 1200 psi. Then length trades off with pressure (Hall [Figure 3]).

A typical LEO cell weight allocation, (Hall [Figure 4]), is divided into thirds: the weight of the positive takes about one-third, the weight of the vessel and the electrolyte also takes about one-third, and the balance of the components take the final third, with tab weight taking about ten percent. The IR drop is between 30 and 60 mV. The optimum for specific energy vs capacity varies with the cell diameter (Hall [Figure 5]). There is no optimum for energy density, (Hall [Figure 6]), but there is a capacity limit set by the maximum practical vessel length.

For a tandem US Air Force stacking or recirculating stacking arrangement (Hall [Figure 7]), there is typically a relationship of improving specific energy vs energy density as shown for a family of 3.5 inch cells. There are some improvements in the back-to-back versus the US Air Force stack arrangements (Hall [Figure 8]).

Various plates have significantly different relative impacts on the IPV. In the chart labelled Ni Electrodes, (Hall [Figure 9]) thicker plates for the same cell capacity mean fewer plates and there is a weight saving.

In (Hall [Figure 9]) labelled Ni Electrodes, the "reference" is Yardney Mantech Plate.

The final sets of curves, (Hall [Figures 10 and 11]), show the optimal values of specific energy that may in theory be attained.

In (Hall [Figure 12]) the specific energy for cells that have been manufactured by Whittaker-Yardney is shown relative to practical state-of-the-art boundaries.

Q. _________: When the capacity is increased how?

A. There is a combination of effects having to do with electrode manufacture: additives, porosity, loading level, and process controls.

Whittaker

PARAMETRICS OF NICKEL-HYDROGEN CELL DESIGN

BY

PETER J. DENONCOURT

ARNOLD M. HALL

WHITTAKER-YARDNEY POWER SYSTEMS

PAWCATUCK, CT 02891

FIGURE 1. HALL

TYPICAL 3.5" DIA. CELL TRADE-OFF

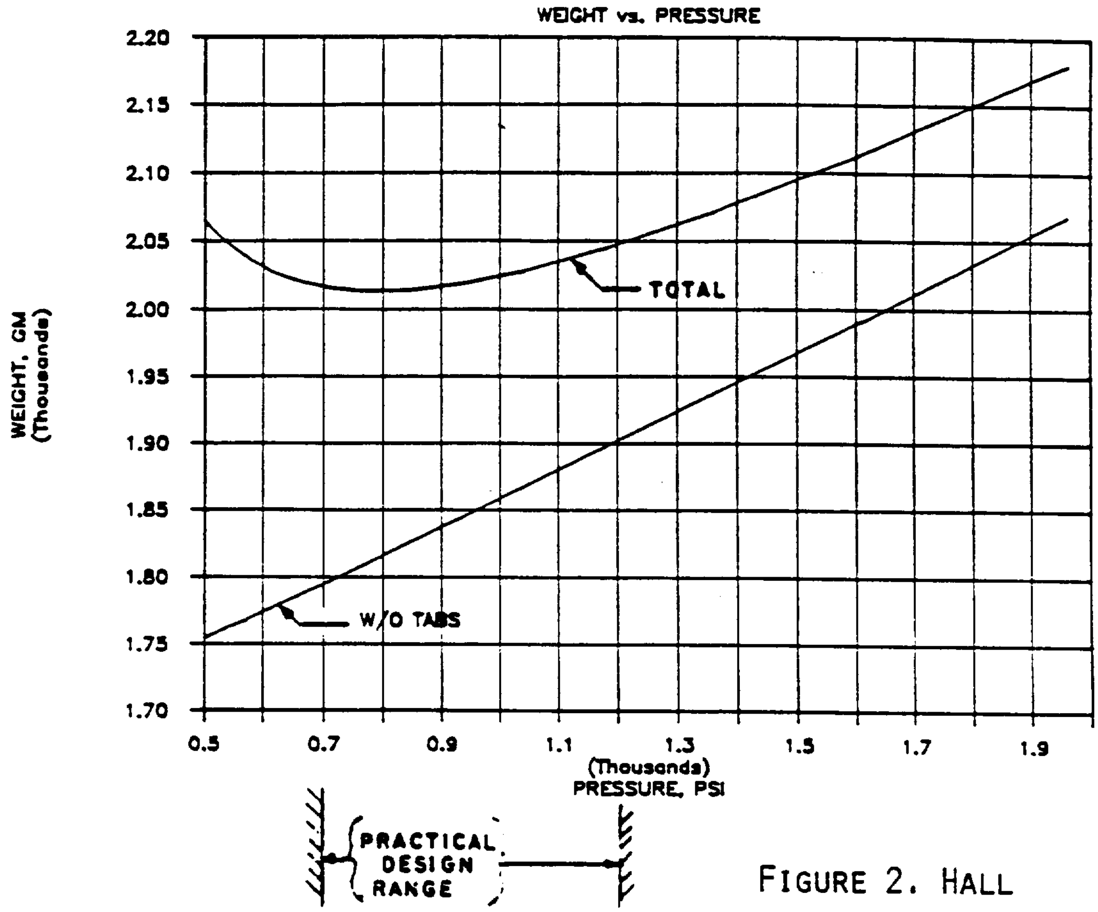


FIGURE 2. HALL

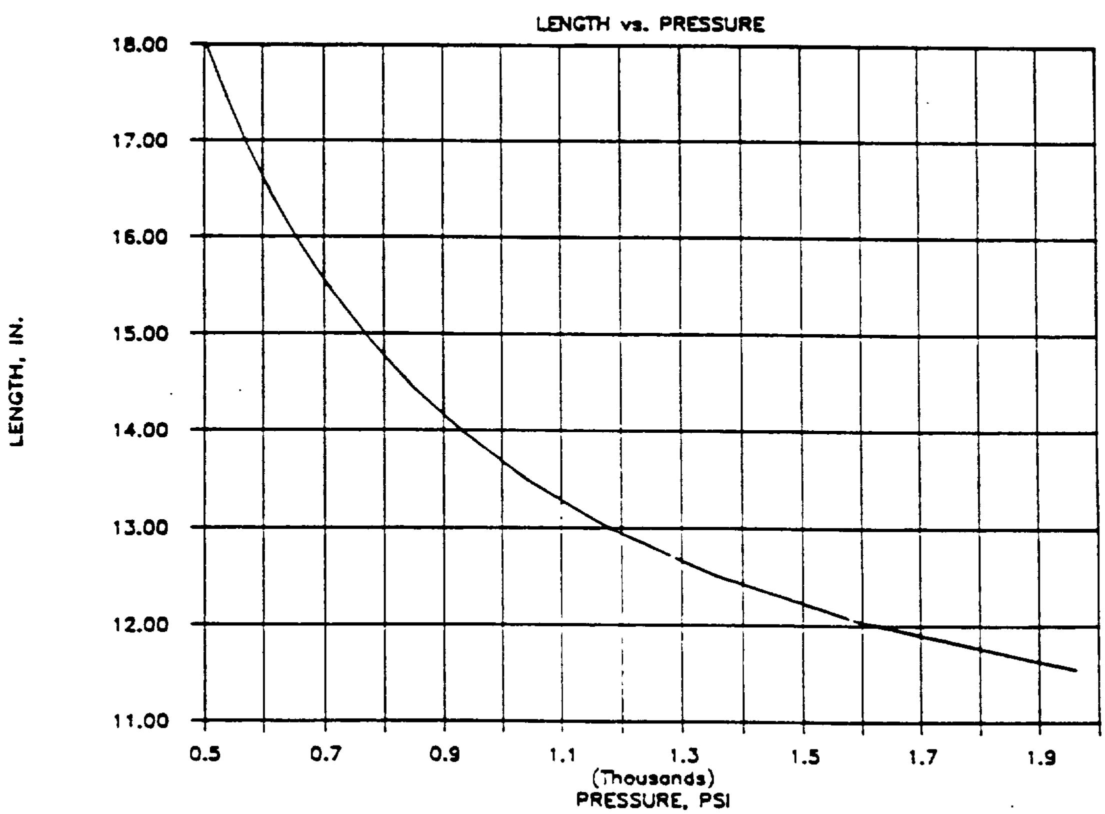


FIGURE 3. HALL

TYPICAL LEO CELL
WEIGHT ALLOCATION

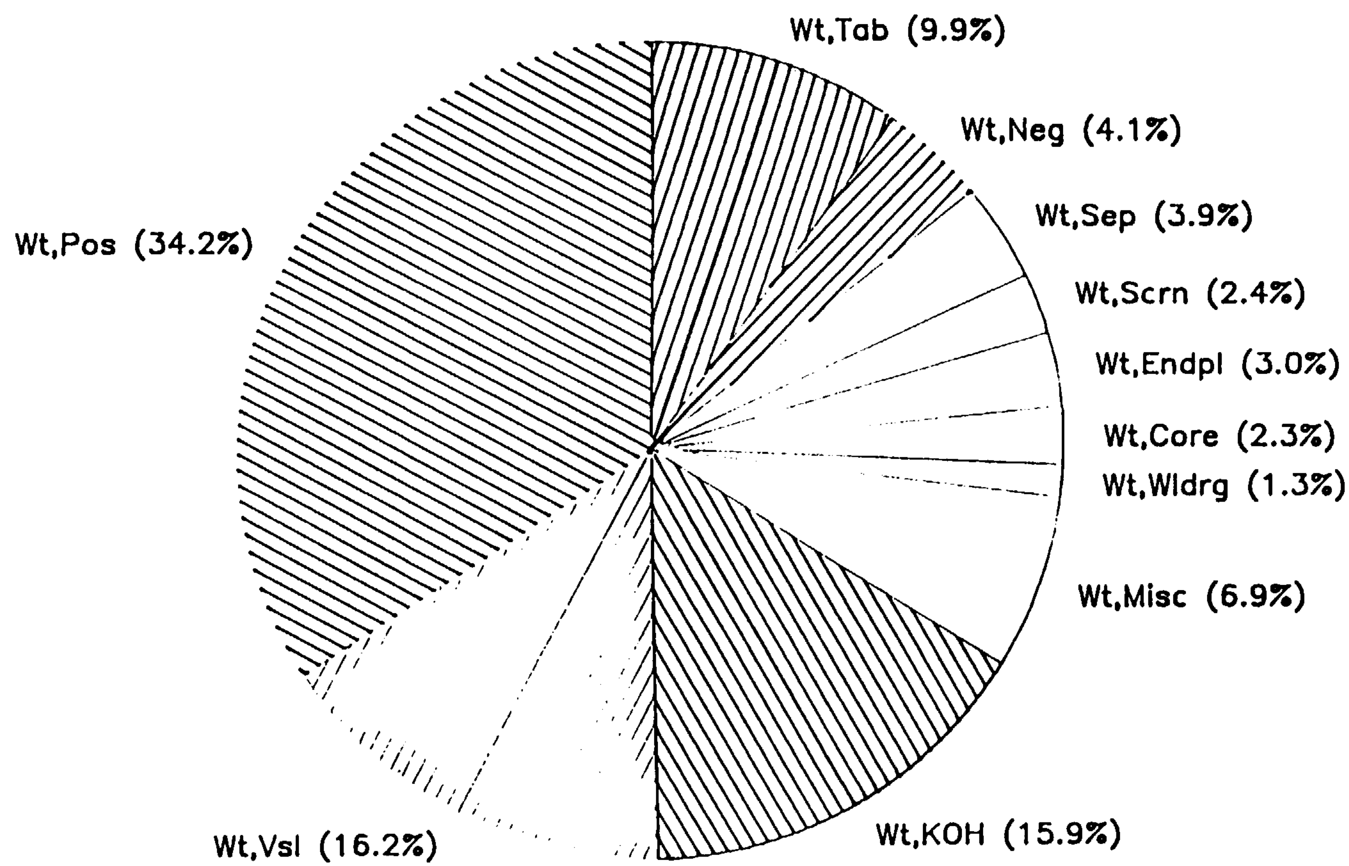


FIGURE 4. HALL

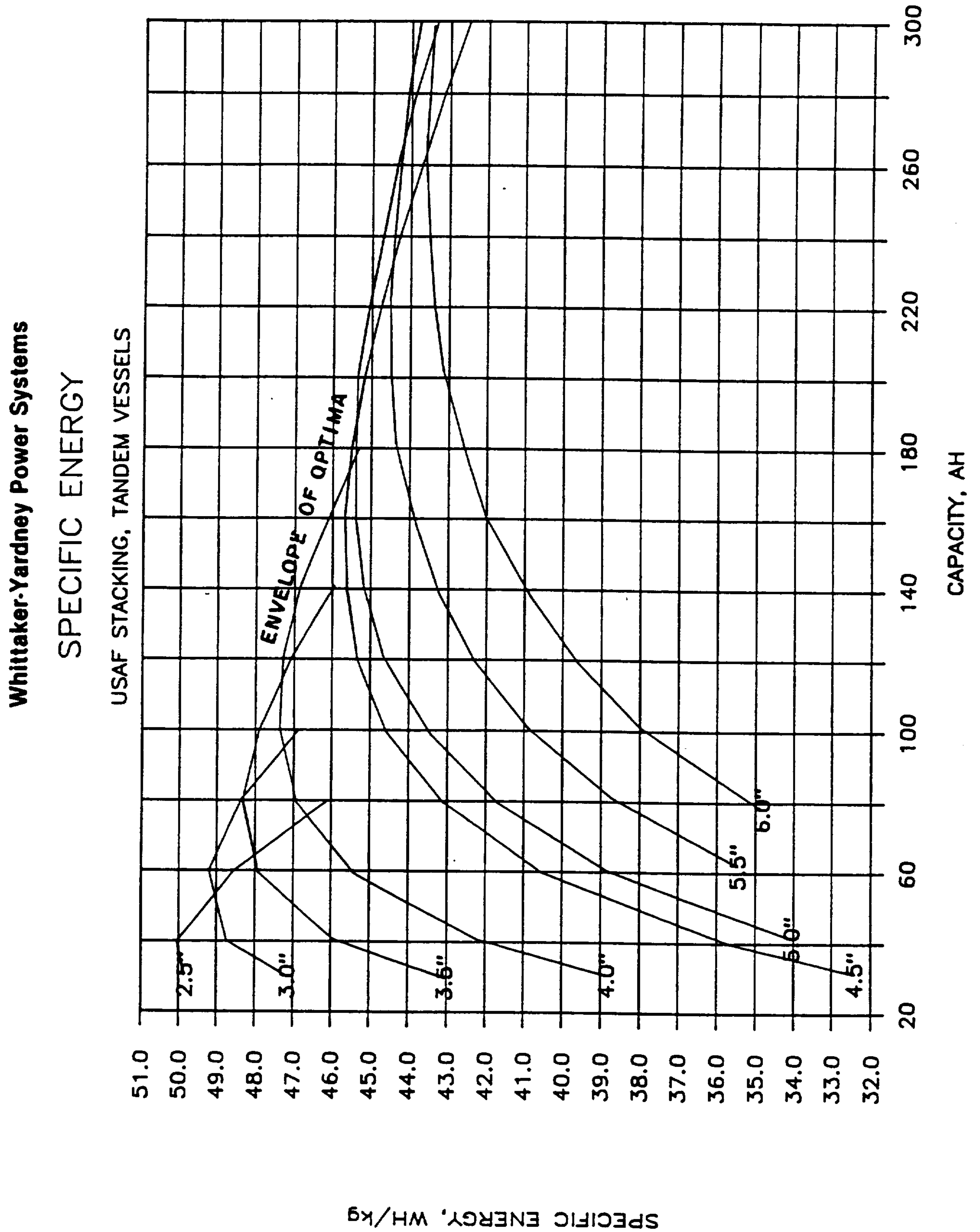


FIGURE 5. HALL

Whittaker-Yardney Power Systems

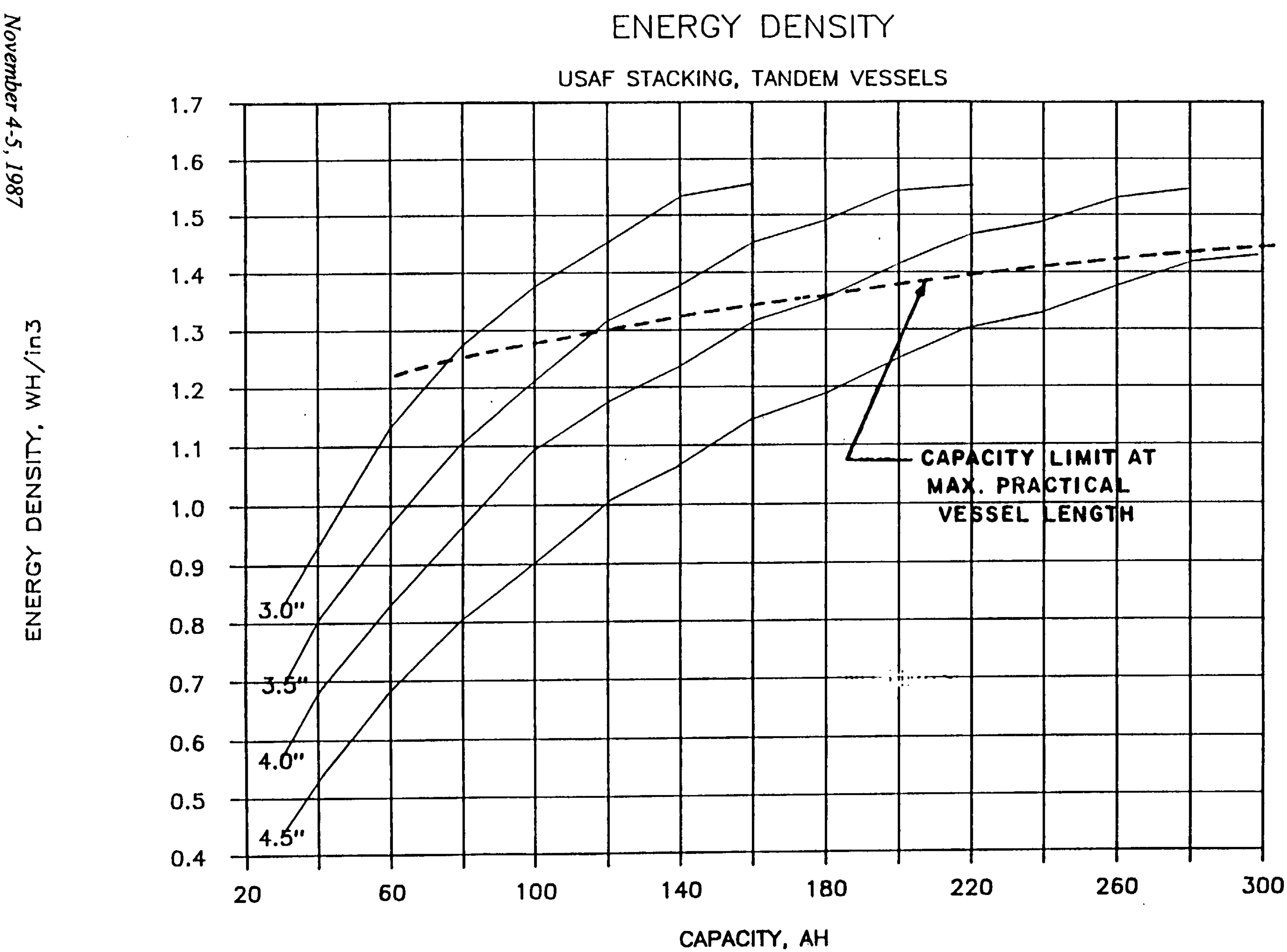


FIGURE 6. HALL

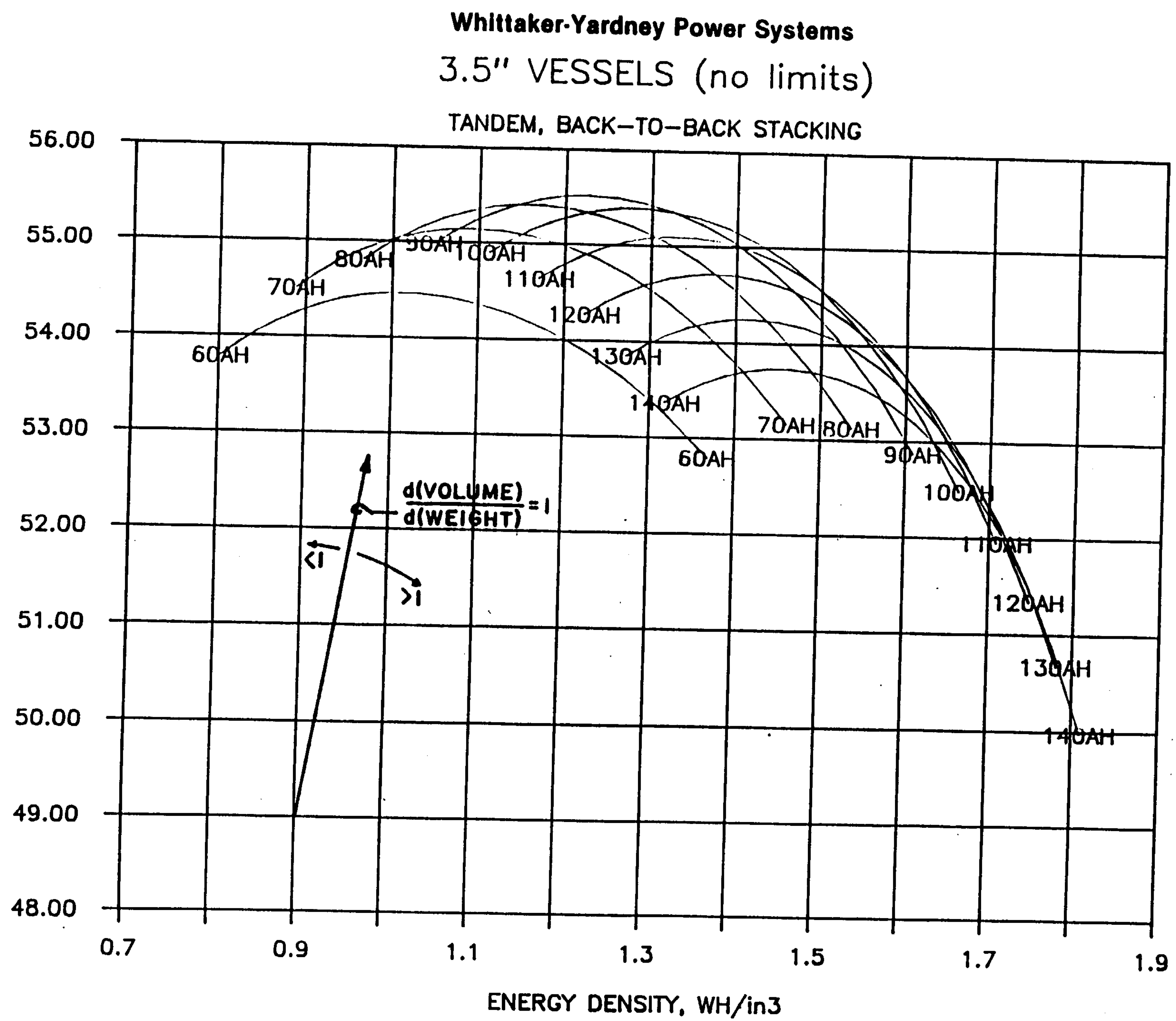


FIGURE 7. HALL

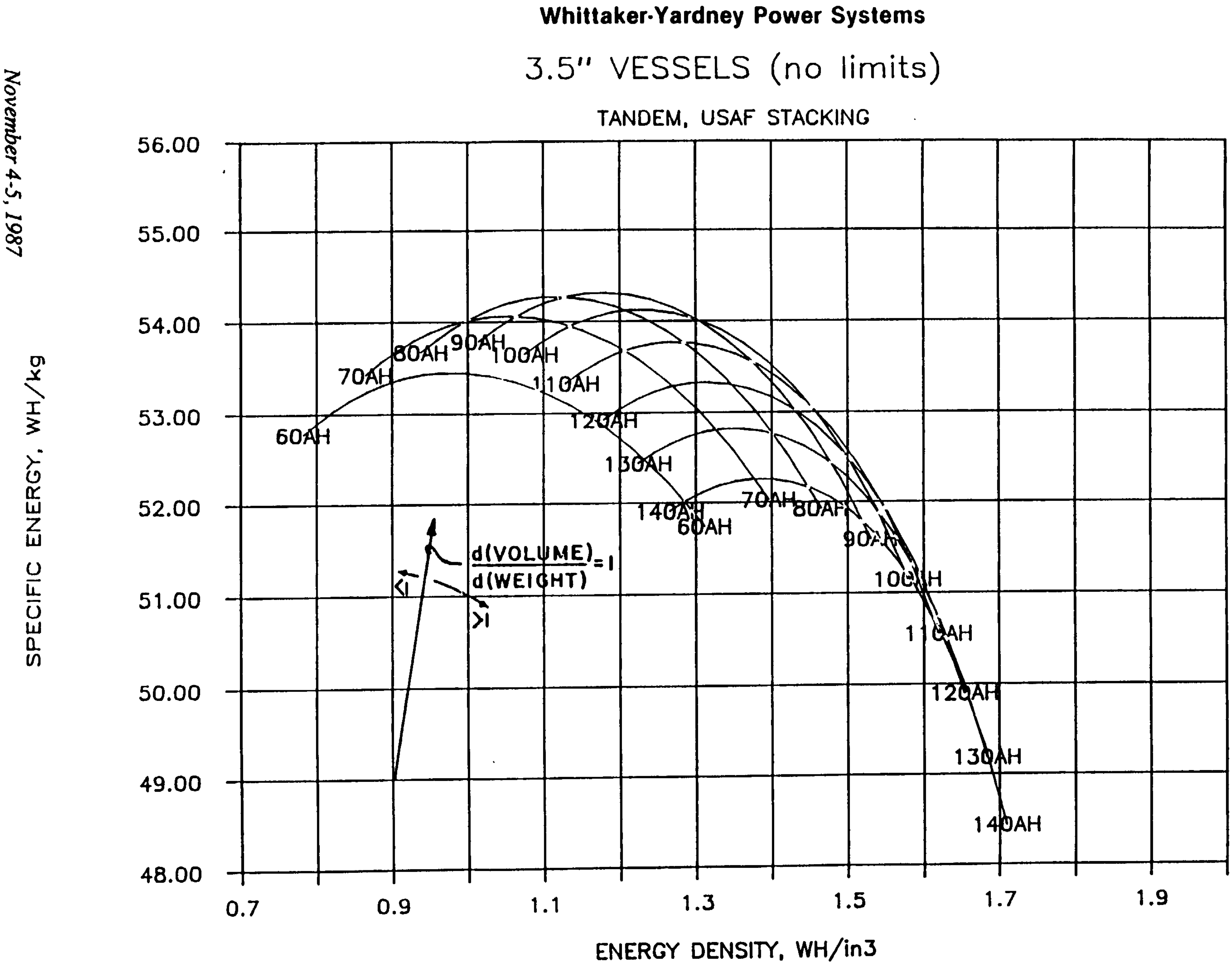


FIGURE 8. HALL

Whittaker-Yardney Power Systems

Ni ELECTRODES

80AH in 3.5" UNIT VESSEL

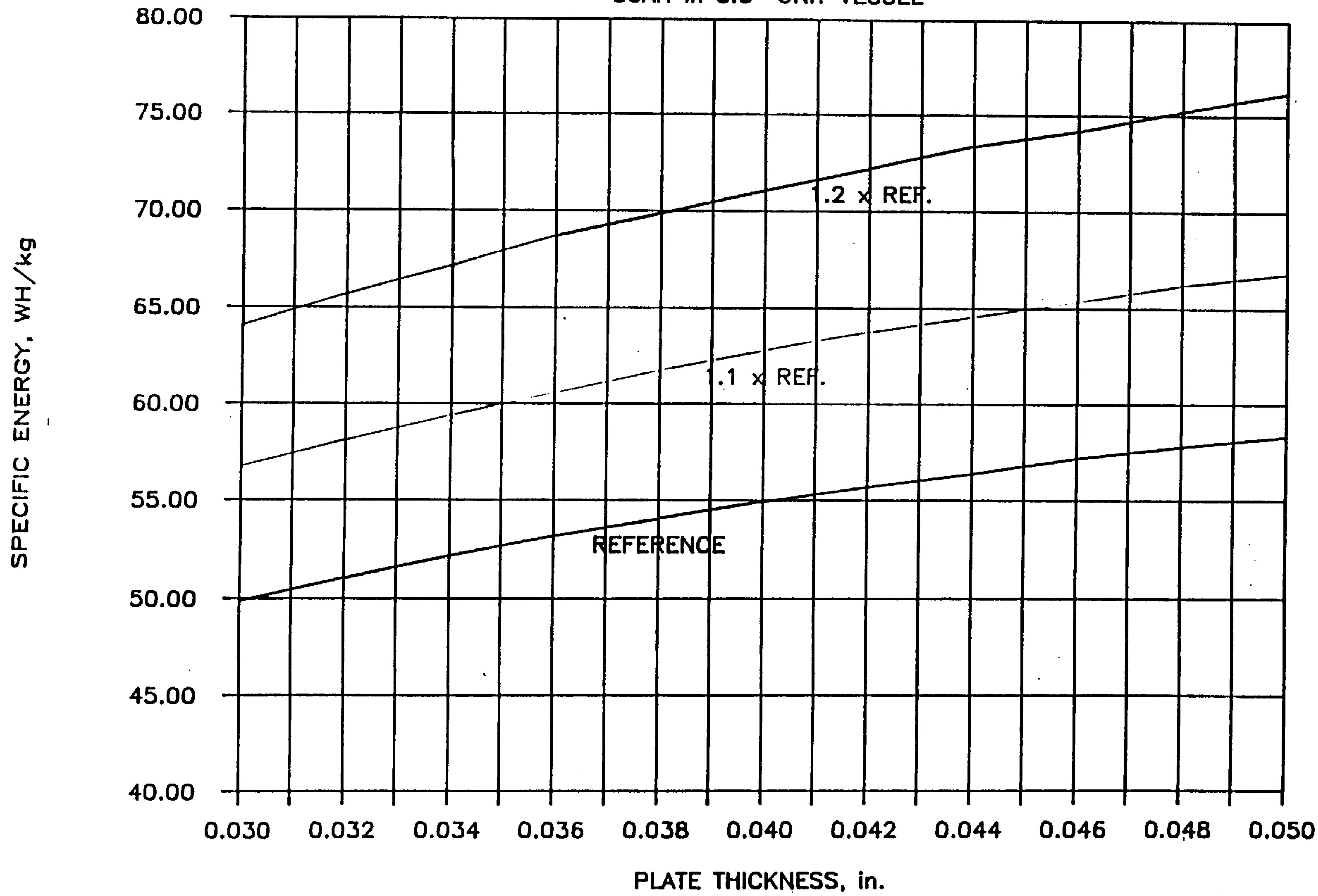
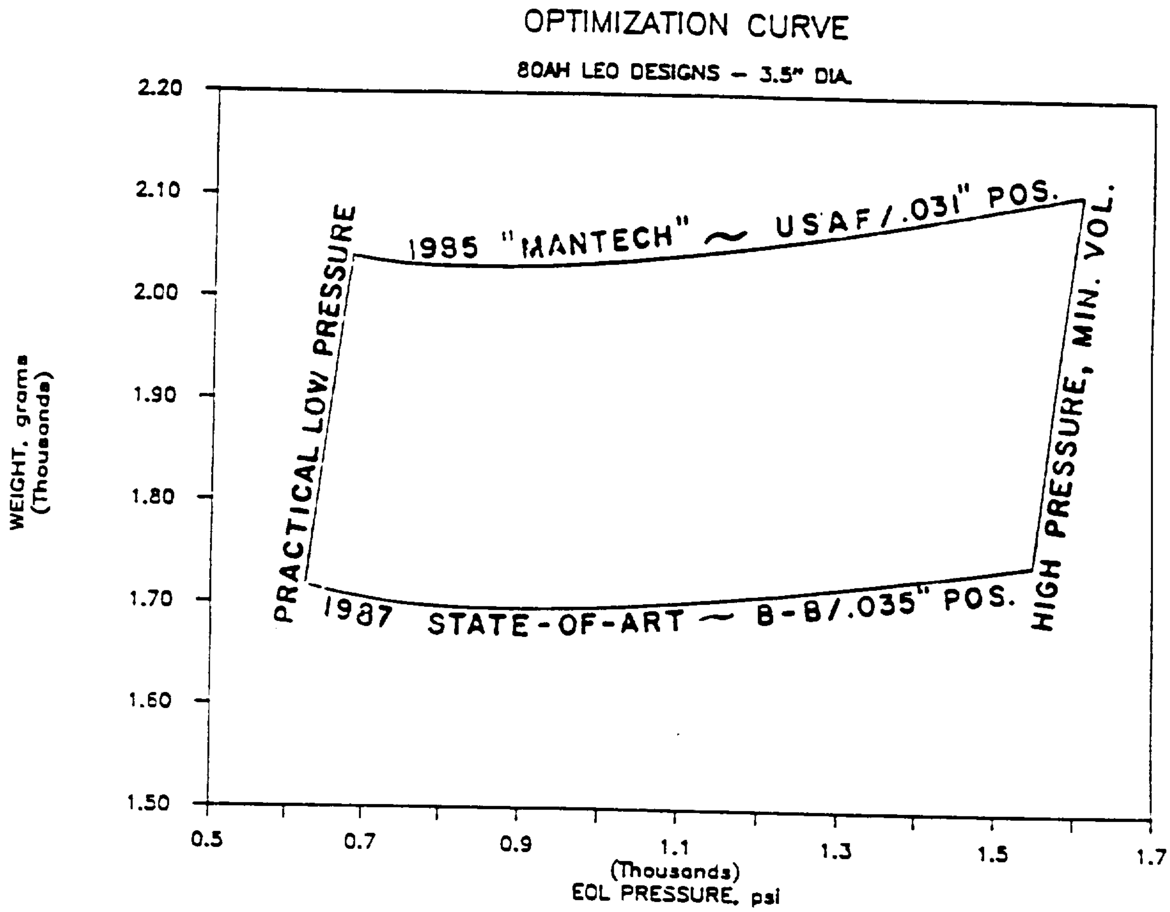


FIGURE 9. HALL



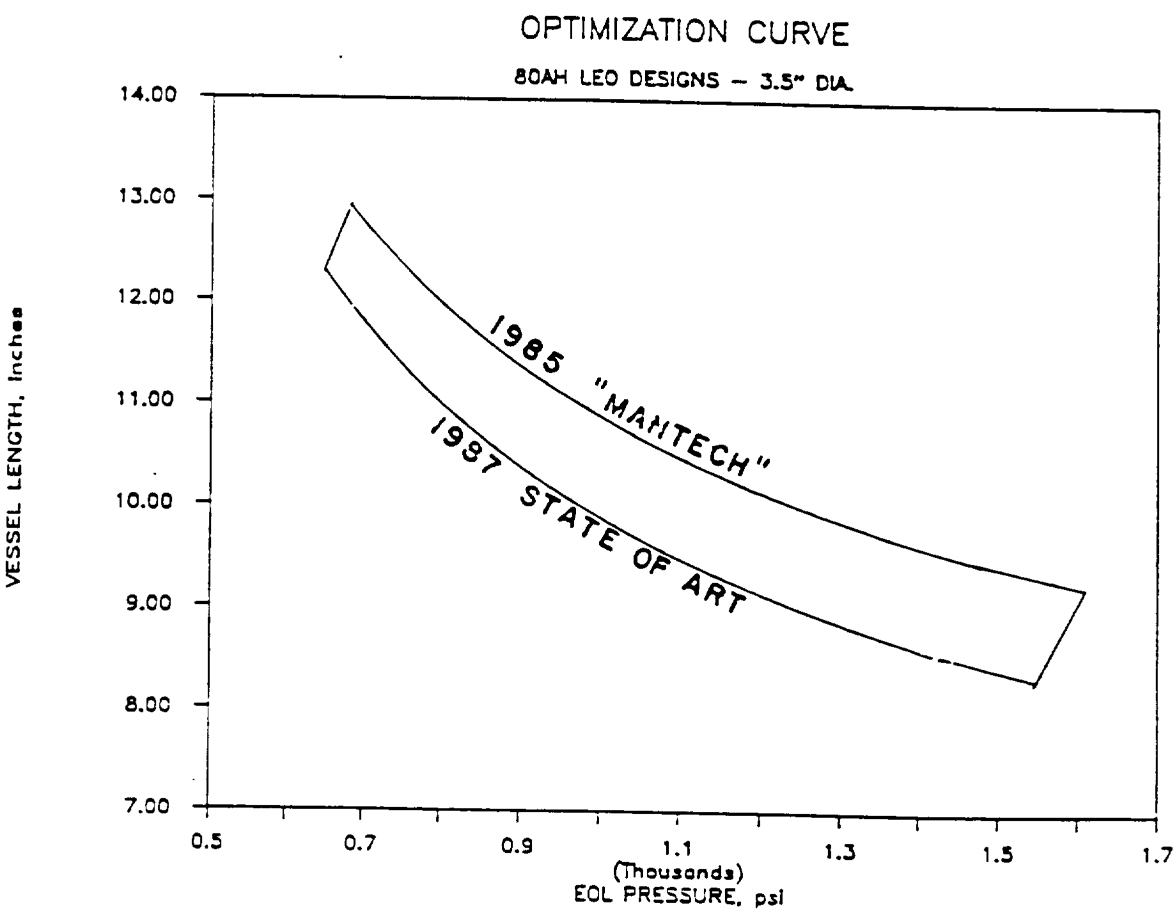


FIGURE 10. HALL

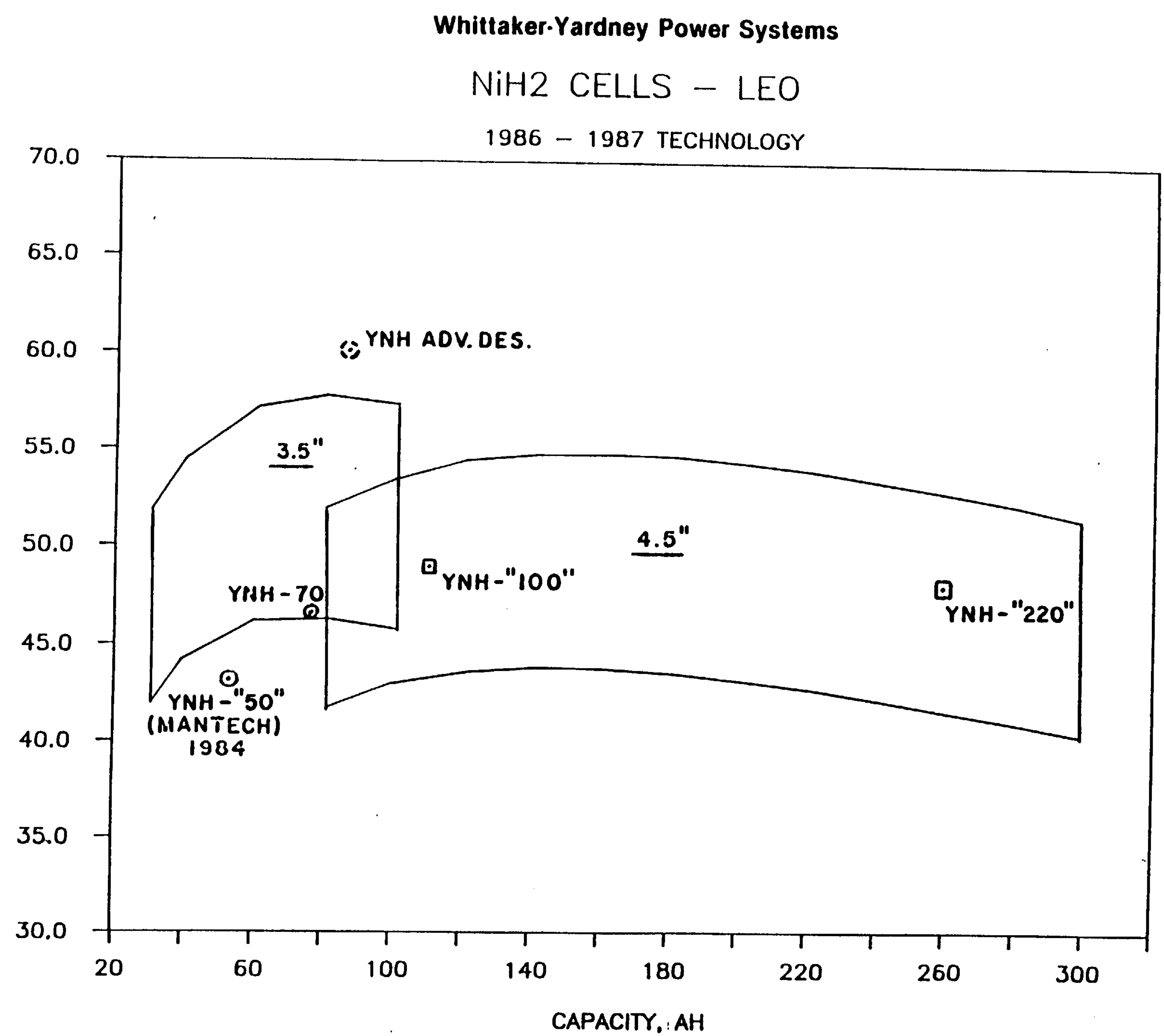


FIGURE 11. HALL

THURSDAY, NOVEMBER 5, 1988
(AFTERNOON SESSION)

"DEVELOPMENTS IN NiH_2 CELL DESIGNS FOR SPACE APPLICATIONS"

JOHN HARVEY

The first speaker was John Harvey (Marconi Space Systems, Portsmouth, England) on "Developments in NiH_2 Cell Designs for Space Applications."

Harvey showed the division of design, development, and manufacture tasks between Marconi and Harwell Laboratory for the NiH_2 cell to fly in geosynchronous orbit (Harvey [Figure 2]). Marconi has used space batteries since the 60's and Harwell started their development of NiH_2 cell in 1975. They combined operations in 1985 to design the NiH_2 cell for geosynchronous applications. Marconi will manufacture the batteries at the end of the development sequence.

Harvey [Figure 3], shows the independent pressure vessel (IPV) cell. The Nickel electrodes are of the sintered type. The pressure vessel is made of Inconel 718. The cell stack is supported at both ends, and the cell is designed for minimum mass.

NASTRAN finite element analyses were performed to verify that the cell will withstand design loads and meet dynamic performance requirements (Harvey [Figure 5]). Single-cell and multi-cell models were used to determine temperature distributions. Twelve cells were manufactured for the tests. Eight cells were put through cycle life tests, and all eight exceeded 1000 cycles.

The capacity for various charge rates on cell number 9 (Harvey [Figure 9]), was a maximum at C/5; capacity for discharge at various rates, (Harvey [Figure 10]), decreased slightly as discharge rate increases; and at various ambient temperatures measured at C/2 discharge after C/10 charge the maximum capacity on cell number 9 was obtained at 10 degrees C ambient (Harvey [Figure 11]).

A common pressure vessel (CPV) NiH_2 cell was studied for ESA (Harvey [Figure 12]). The intent was to make optimum use of the advantages of the CPV configuration. The cell stacks require isolation of the electrolytes, but hydrogen must have free access to all the stacks. A cooling pillar was added to remove heat from the stacks. There is also a feature to accept stack expansion. A spherical pressure vessel is used.

The cell stacks were contained and each container had breathing apertures to provide oxygen management. Each stack had a 50 amp-hour capacity. NASTRAN finite-element analysis of stress showed that the cells can stand the design loads and meet the stiffness requirements.

Good heat transfer was achieved by having a small gap between components in the heat path. The temperature changes were acceptable. The CPV's are being tested now, and results will be presented later.

In summary, (Harvey [Figure 15]), all analyses have been done by computer modeling. The IPV cell design and performance have been confirmed, and the CPV cell has been designed and its performance is being assessed.

Q. _____: The CPV design has a metal core. Is there an electrical insulator between the core and the plates?

A. Yes

Q. Miller (Eagle-Picher): What plate separator system do you use?

A. Zircon Yttrium cloth.

Q. Chang (Ford Aerospace): Was the IPV natural frequency measured?

A. Yes, it was tested to specification but the resonant frequency inside was not measured.

Q. Badcock (Aerospace Corp.): Do you need to compensate for different electrode pair resistance when both terminals are at one end of the cell?

A. It's not a problem--Harwell would have to respond to this.

Q. Badcock (Aerospace Corp.): How do you verify that flaw size is controlled in the weld and in the parent material?

A. The structural people have studied this.

Q. George (NASA/MSFC): Regarding the natural frequency measurements--are there no plans to measure the natural frequency of the stack?

A. We have a theoretical value.

DEVELOPMENTS IN NICKEL HYDROGEN CELL DESIGN

FOR SPACE APPLICATIONS

J.M.Harvey

Marconi Space Systems Limited

FIGURE 1. HARVEY

DESIGN DEVELOPMEMT and MANUFACTURE

Marconi Space Systems	Harwell Laboratory
Cell structural design	Research on cell stacks
Design analysis	Stack process development
Stress	Stack manufacture
Dynamic	Stack assembly
Thermal	Cell filling
Environmental evaluation	Electrical performance testing
Flight cell manufacture	Life testing

FIGURE 2. HARVEY

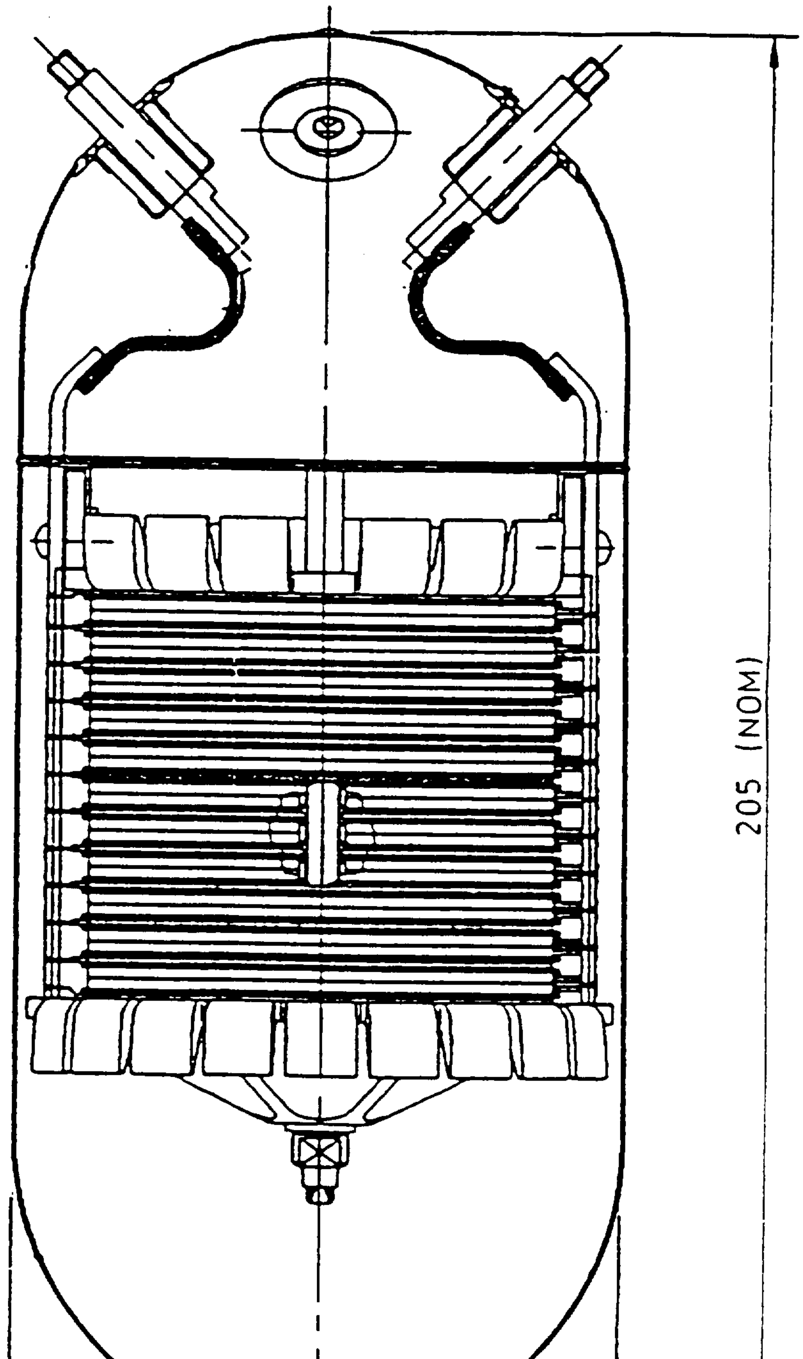


FIGURE 3. HARVEY

Marconi

REQUIREMENTS SUMMARY

Capacity: 50 AH nominal

Life: Greater than 2000 charge/discharge cycles at C/2 and 70% depth of discharge

Load: Greater than 200 A for 5 sec. at top of charge

Mid discharge voltage: Greater than 1.23 v

Vibration: Sine and random

Constant acceleration: 20 g

FIGURE 4. HARVEY

Marconi

IPV CELL DESIGN ANALYSIS

'NASTRAN' finite element analysis to confirm that the Nickel Hydrogen cell will withstand the design loads of pressurisation, constant acceleration, vibration and temperature.

'NASTRAN' finite element analysis to confirm that the dynamic performance of the Nickel Hydrogen cell is met.

'SINDA' model to confirm the thermal performance of the Nickel Hydrogen cell and that of cells mounted in a battery structure.

FIGURE 5. HARVEY

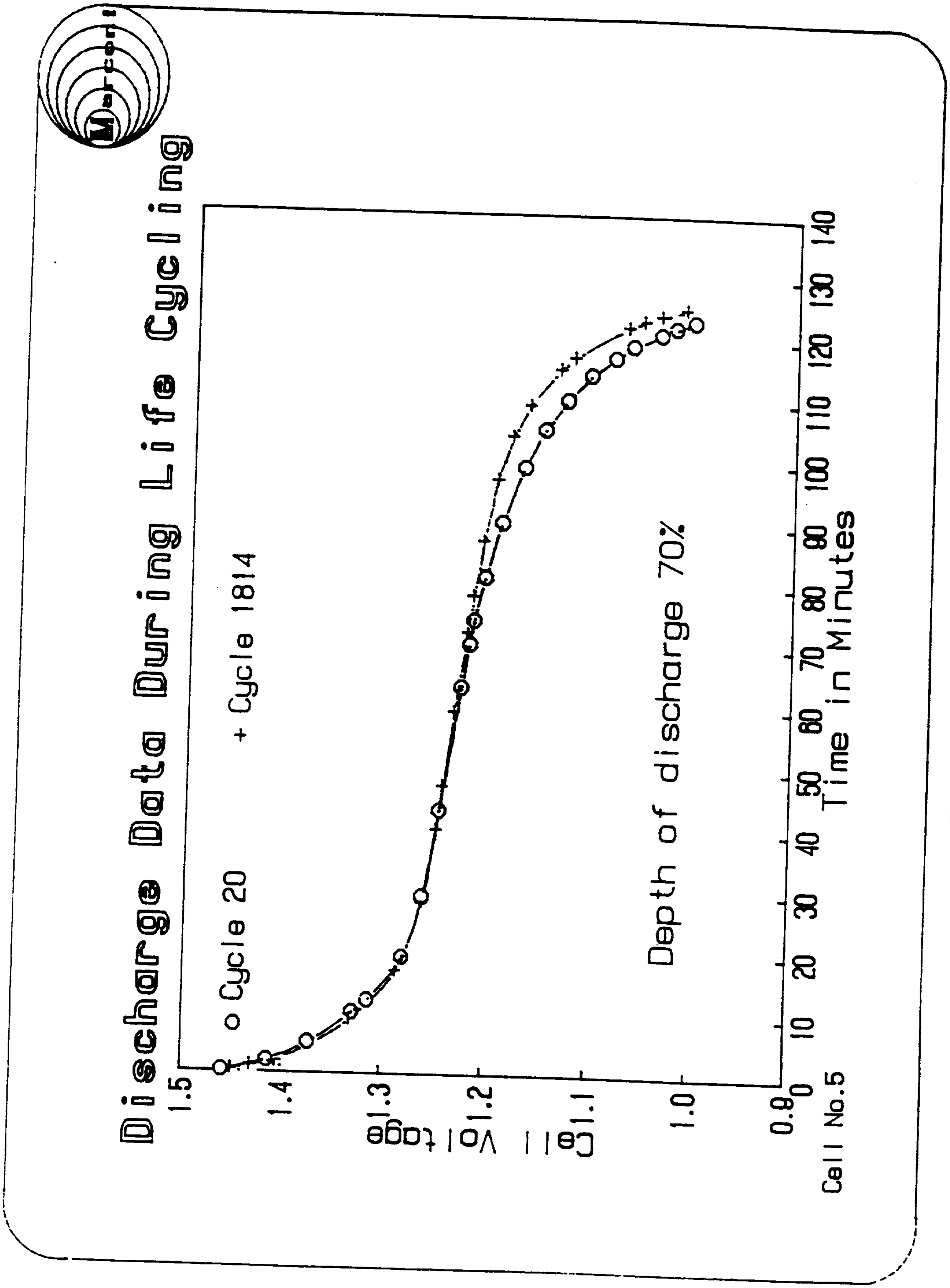


FIGURE 6. HARVEY

Cycle life test voltages

Cycle No.	27	61	293	517	747	1091	1573
Mid Charge	1.515	1.517	1.517	1.517	1.514	1.521	1.522
End of Charge	1.624	1.618	1.614	1.607	1.604	1.610	1.607
Mid Discharge	1.248	1.245	1.250	1.256	1.260	1.260	1.260
End of Discharge	1.181	1.161	1.163	1.171	1.174	1.172	1.168

Cell No.5

FIGURE 7. HARVEY

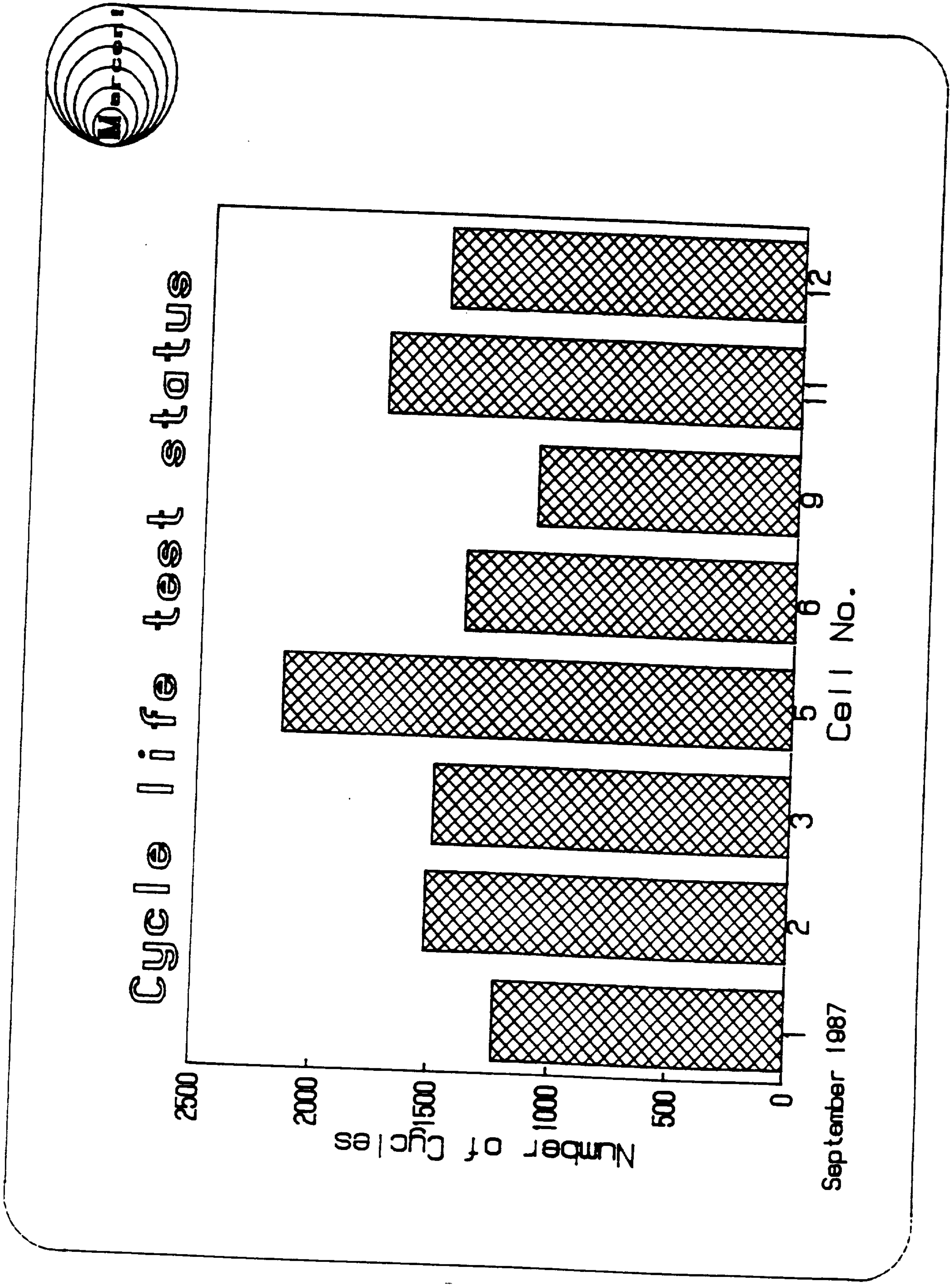


FIGURE 8. HARVEY

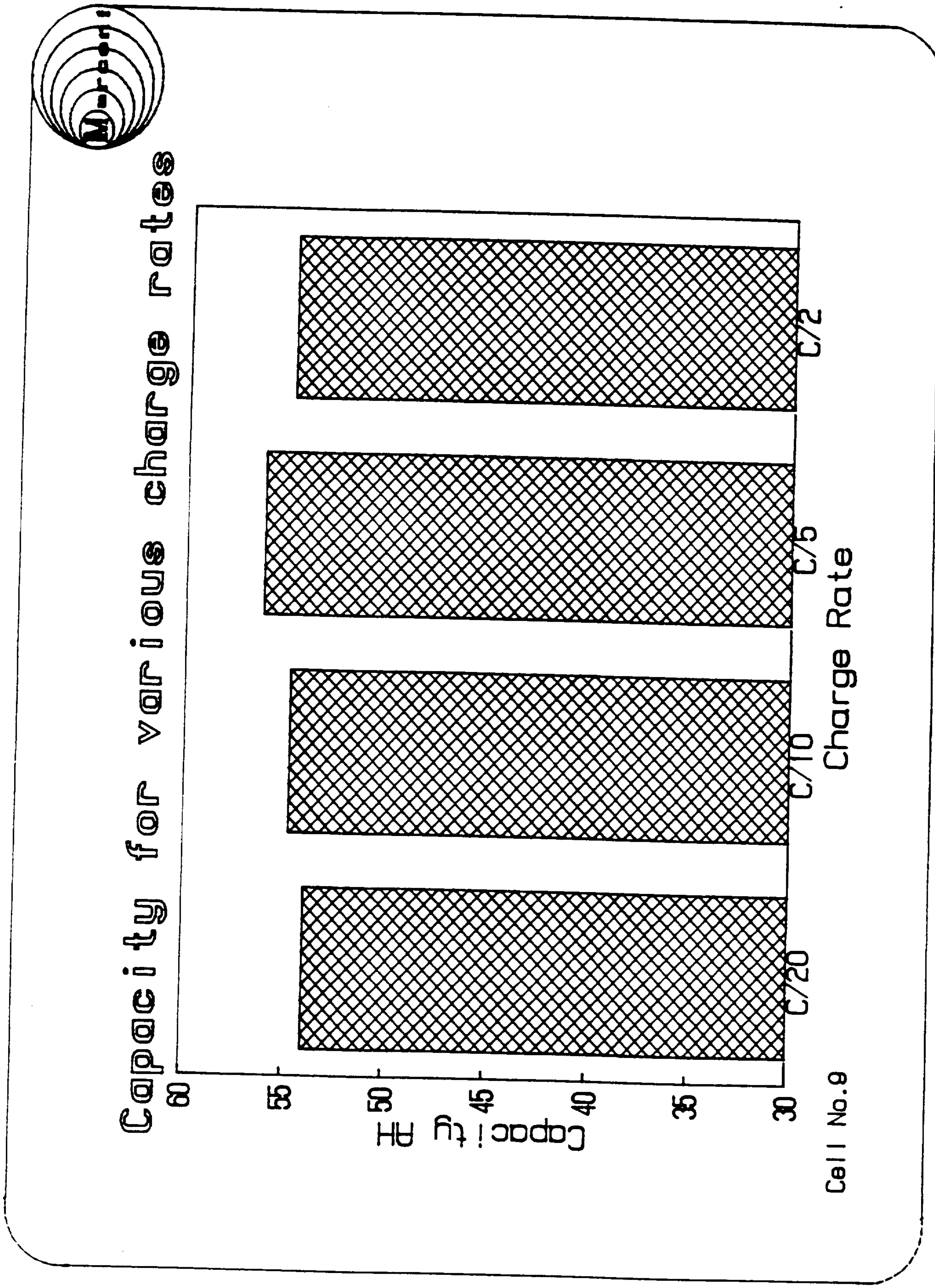


FIGURE 9. HARVEY

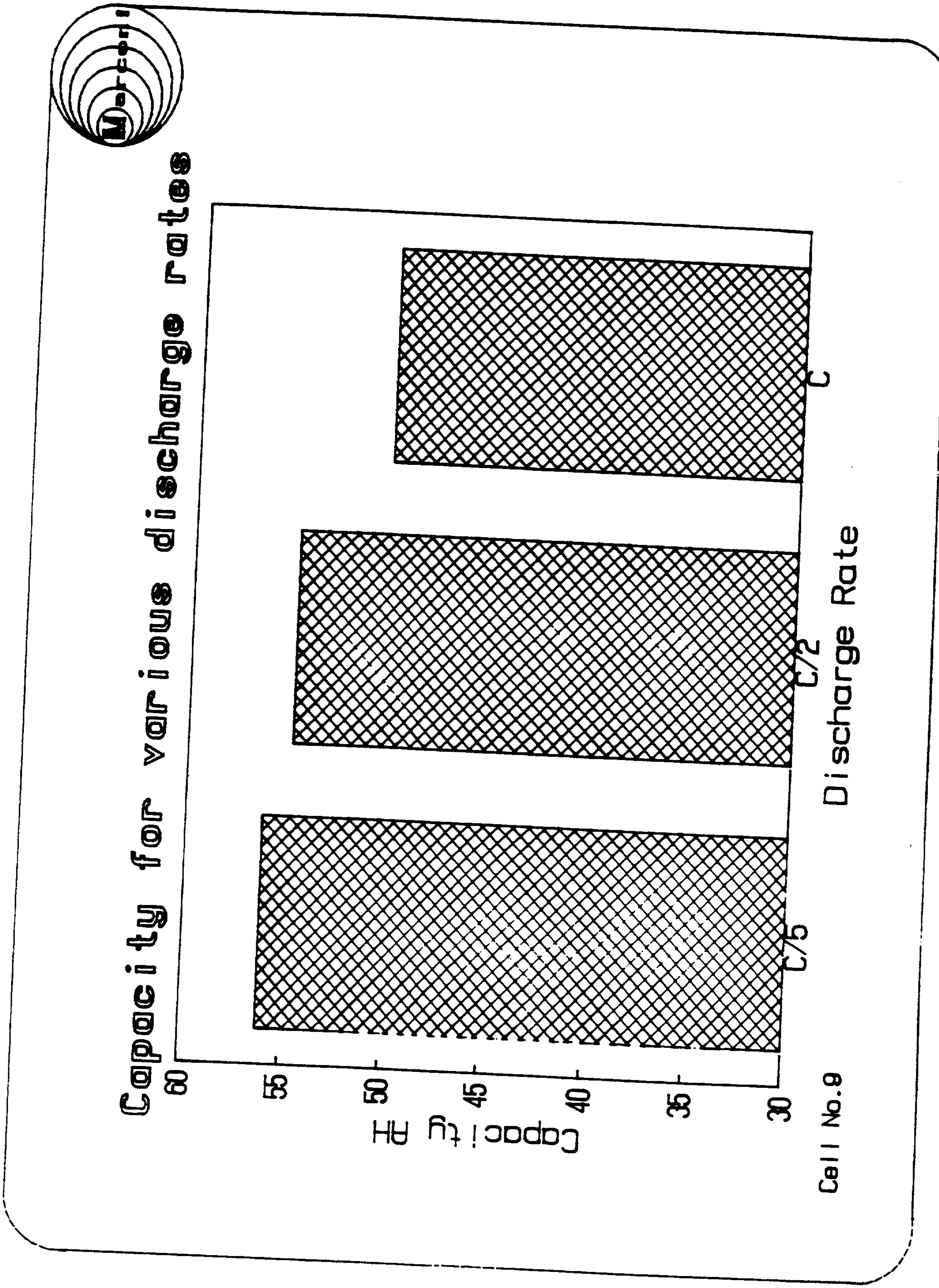


FIGURE 10. HARVEY

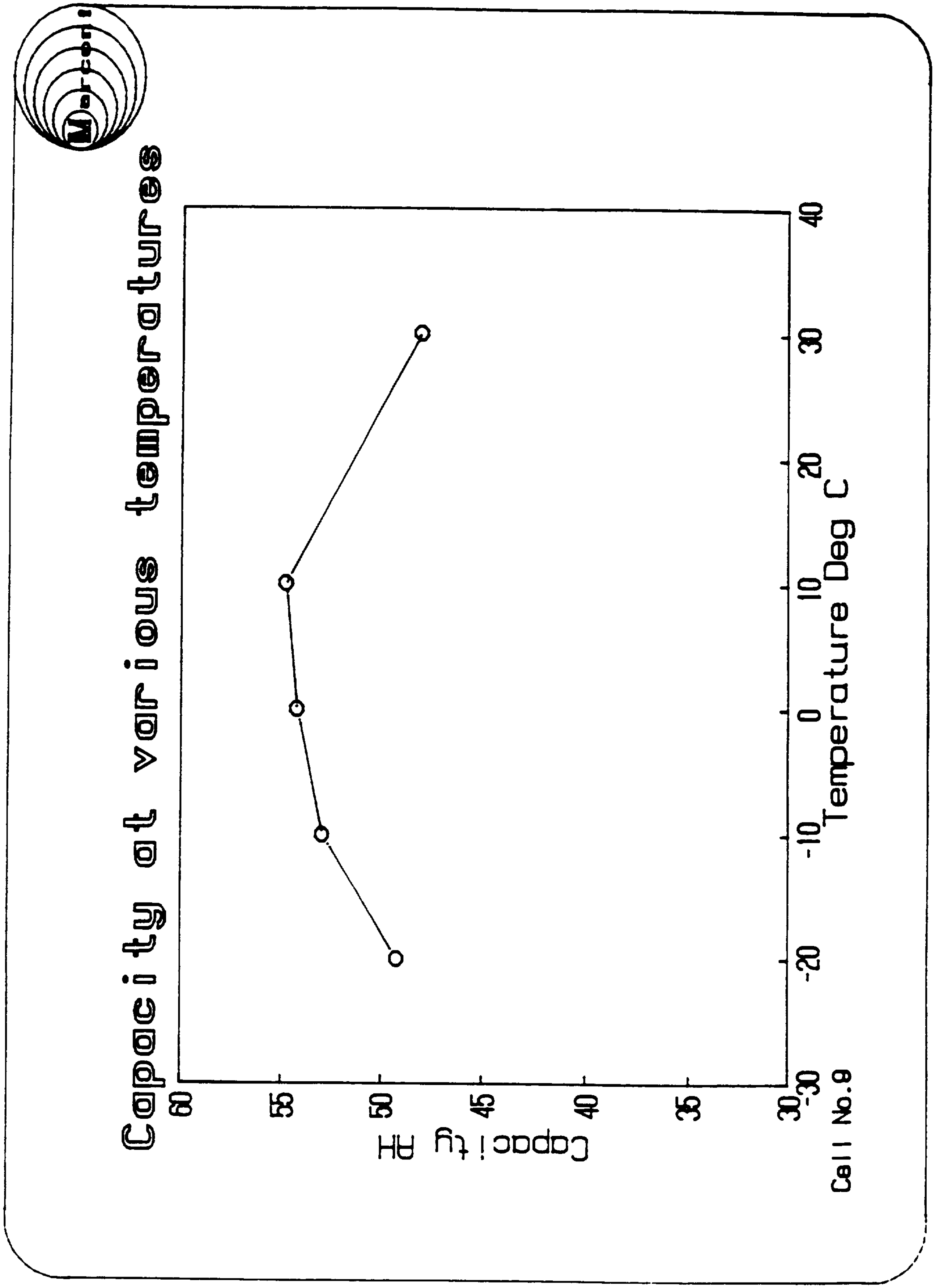


FIGURE 11. HARVEY

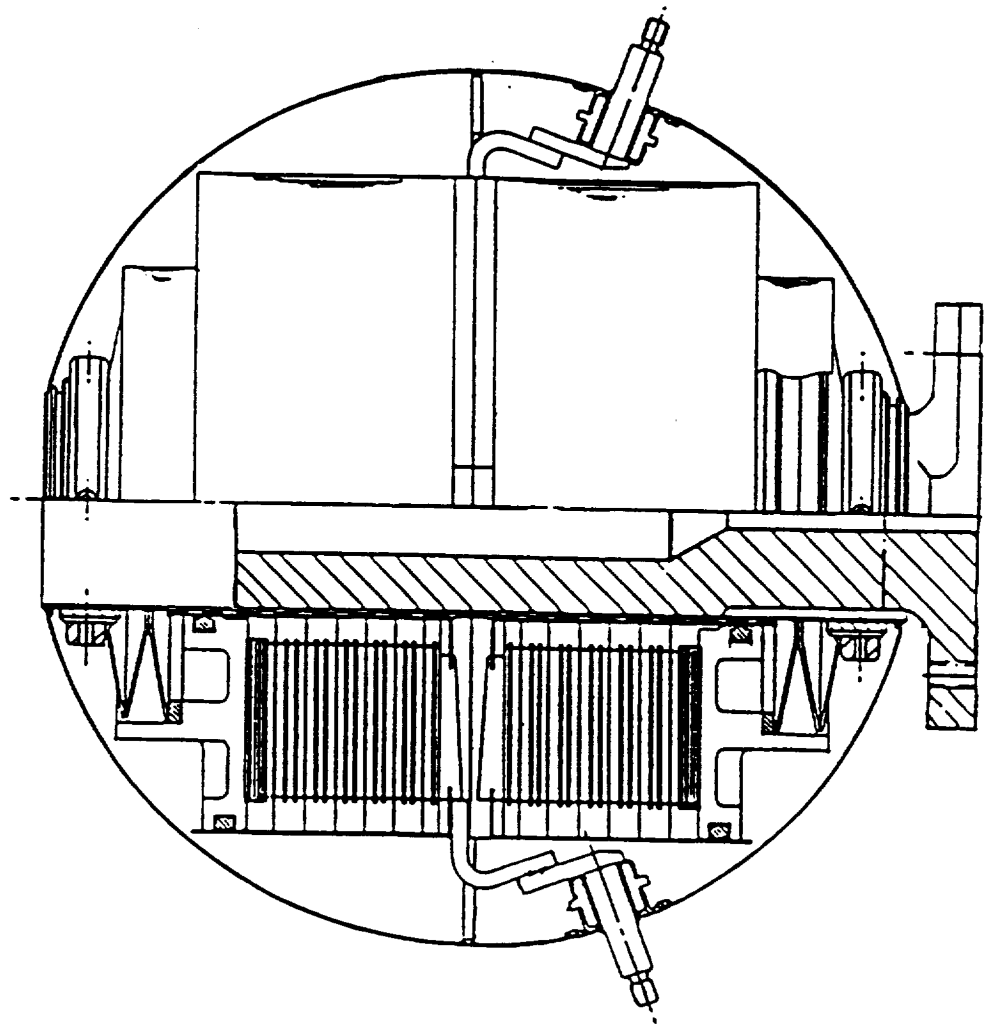


FIGURE 12. HARVEY

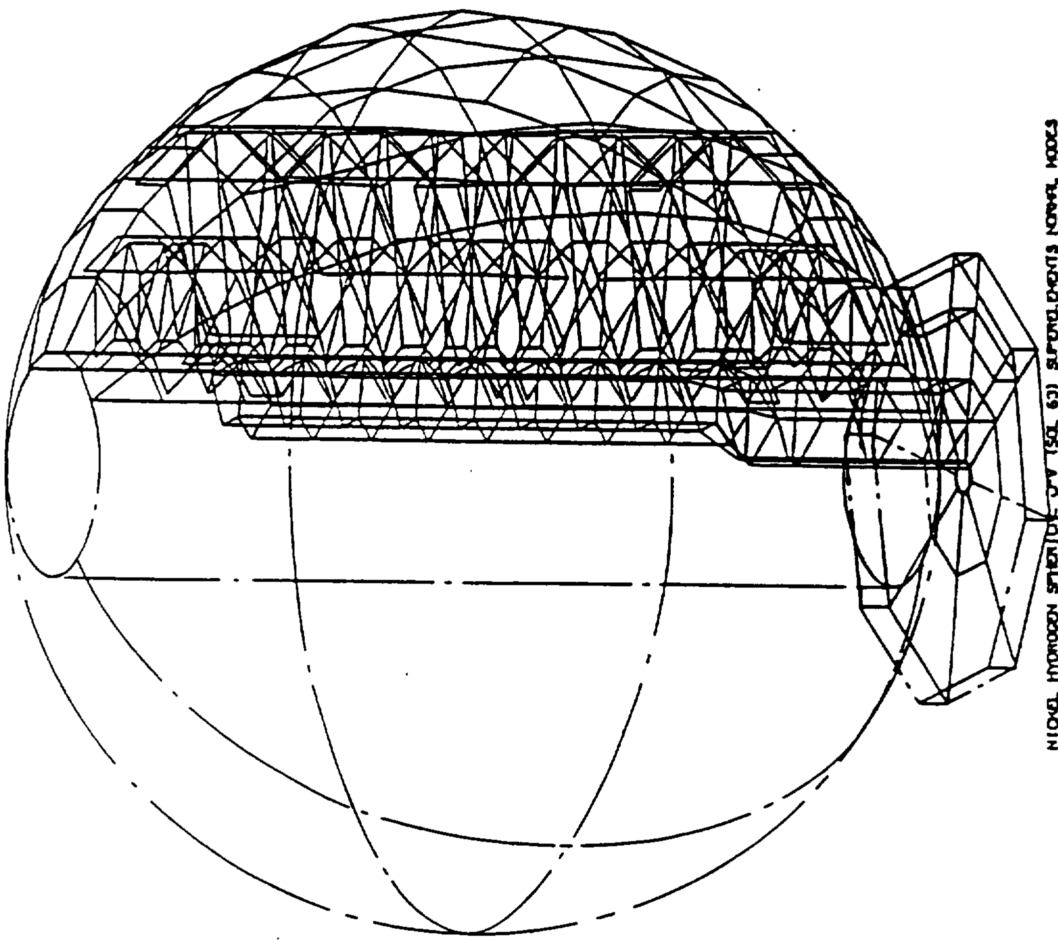


FIGURE 13. HARVEY

CPV DESIGN EVALUATION

Stress analysis

Dynamic analysis

Thermal analysis

Performance tests

FIGURE 14. HARVEY

SUMMARY and CONCLUSIONS

Cells designed as satellite structures

Computer modelling aids design feature investigation

IPV cell development complete and performance confirmed

Advanced CPV cell has been designed and performance is being assessed

FIGURE 15. HARVEY

"PROGRESS IN THE DEVELOPMENT OF A LOW COST NiH_2 BATTERY"

JACK SINDORF

Jack Sindorf (Johnson Controls) described "Progress in the Development of a Low Cost NiH_2 Battery."

Developmental effort on a terrestrial version of the nickel hydrogen battery, funded through Sandia, has resulted in a Common Pressure Vessel (CPV) design costing much less than the Ni/H_2 battery used in communication satellites. A 7 kWh battery was fabricated for autonomous photovoltaic applications. A 30 year life and zero maintenance are projected. The new battery has 4 CPV's connected with a common manifold. There are ten cells in each CPV. The system provides 7 kWh at 24 volts.

An improved aerospace battery consists of 27 cells in a CPV. Each cell has nine cell-modules, and each cell-module has 2+ and 2- electrodes bound in a back-to-back configuration by the diffusion screens. Hydrogen negative electrodes offer a significant weight advantage over cadmium electrodes. The CPV battery has a final weight of 21.93 kg, giving it a 26% weight reduction over a corresponding IPV battery (Sindorf [Figure 15]). 60 Whrs/kg are projected for the CPV battery, and the cost is projected to 1/15 that of the Intelsat V IPV battery (Sindorf [Figure 16]).

With a 72 battery/year production rate, there could be a 15-to-1 cost reduction, 50 percent improved energy efficiency, and 3-to-1 volume reduction (Sindorf [Figure 16, 17, and 18]). Contributing to the cost reduction are the CPV, less expensive catalysts in the negative, improved nickel electrodes, and high-volume manufacturing.

Q. Koehler (Ford Aerospace): Where do the diodes go?

A. Dunlop (COMSAT): Inside the pressure vessel.

Q. Koehler (Ford Aerospace): Is cooling provided by a pumped fluid?

A. That is the preferred option.

Q. Koehler (Ford Aerospace): How about including the weight of the fluid in the weight breakdown?

A. Dunlop (COMSAT): We should do this for the space version and there would be a weight penalty.

Q. Koehler (Aerospace): Any vibration work on the CPV

A. Not yet.

BACKGROUND

SANDIA INITIATED DEVELOPMENTAL PROGRAM

- -TERRESTRIAL VERSION NICKEL HYDROGEN
- -MAINTAIN AEROSPACE FEATURES
- -REDUCE COST

CONSIDERABLE PROGRESS MADE

KNOWLEDGE GAINED APPLICABLE TO BATTERIES FOR AEROSPACE APPLICATIONS

FIGURE 1. SINDORF

FIGURE 2. SINDORF

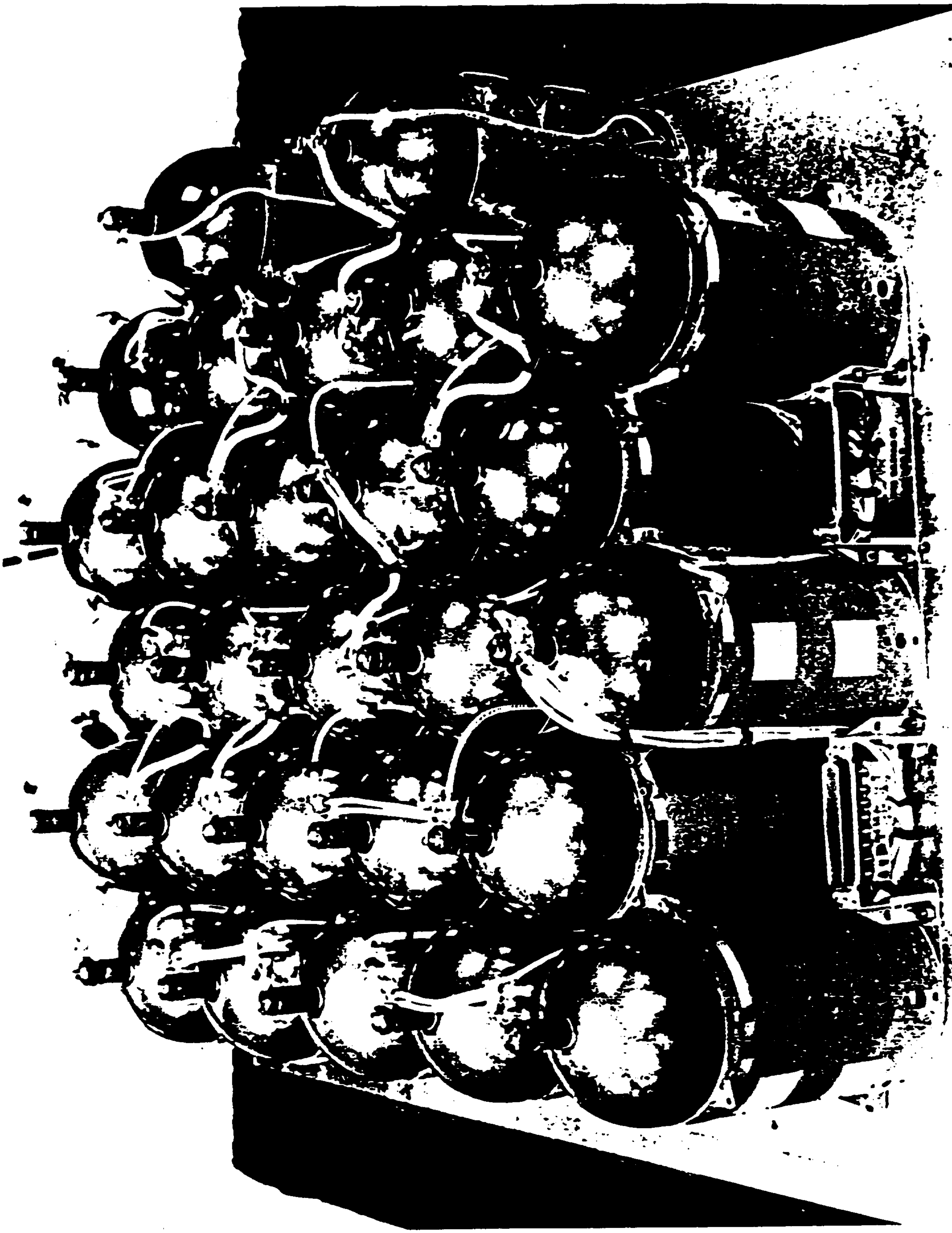


FIGURE 3. SINDORF

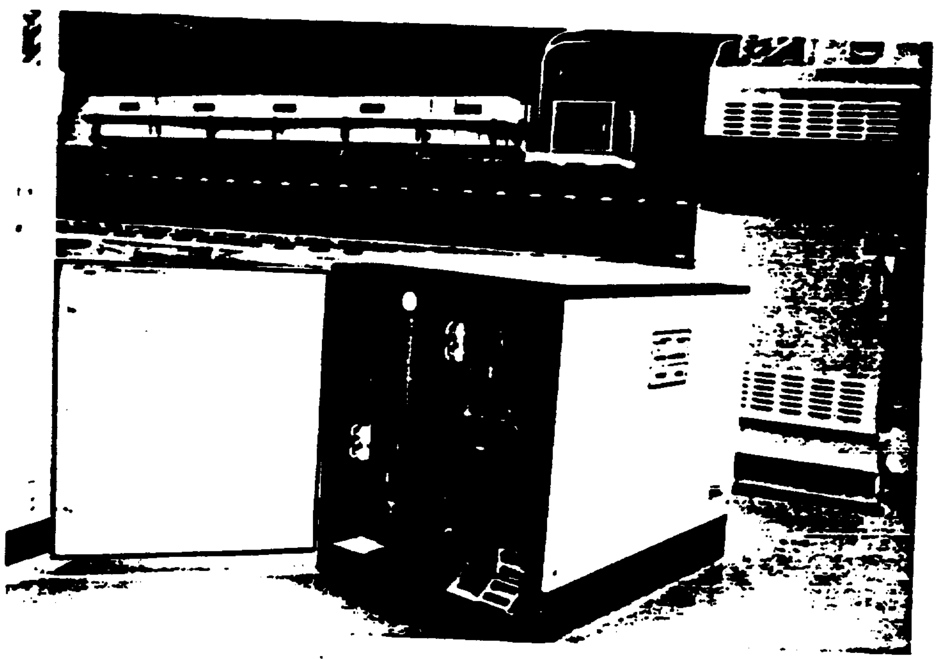


FIGURE 4. SINDORF

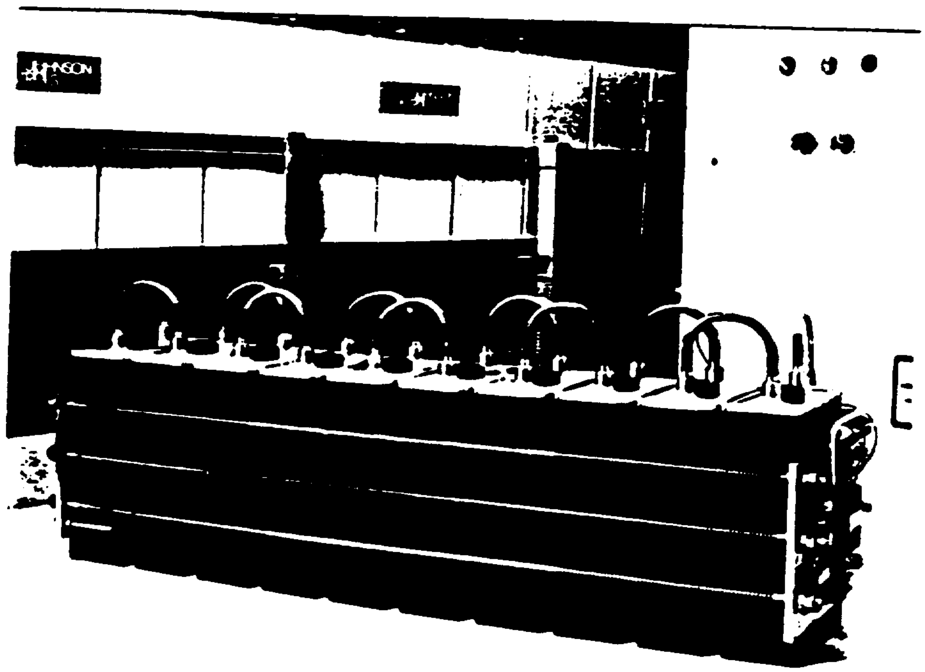


FIGURE 5. SINDORF

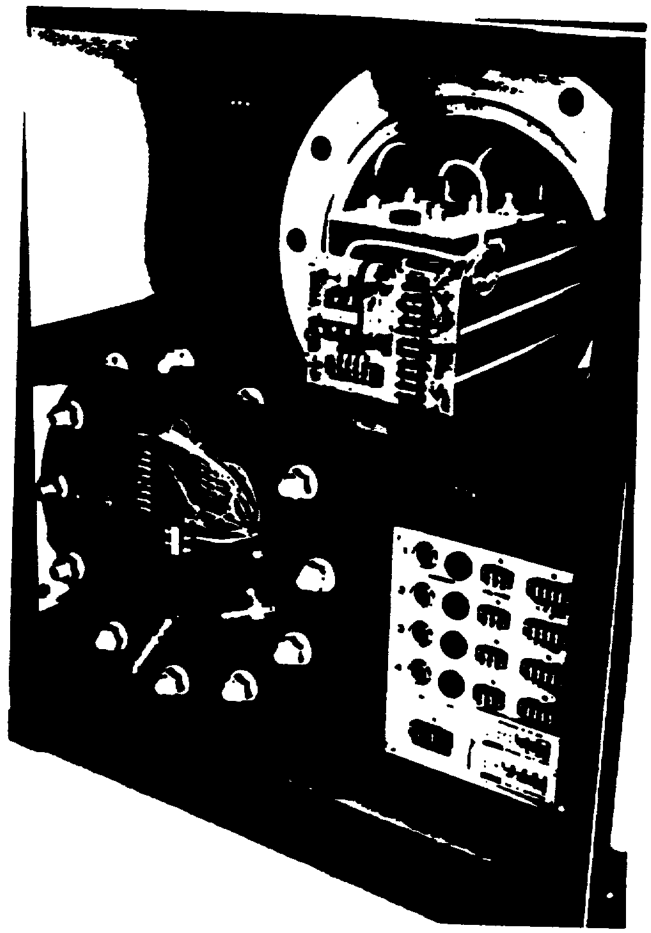


FIGURE 6. SINDORF

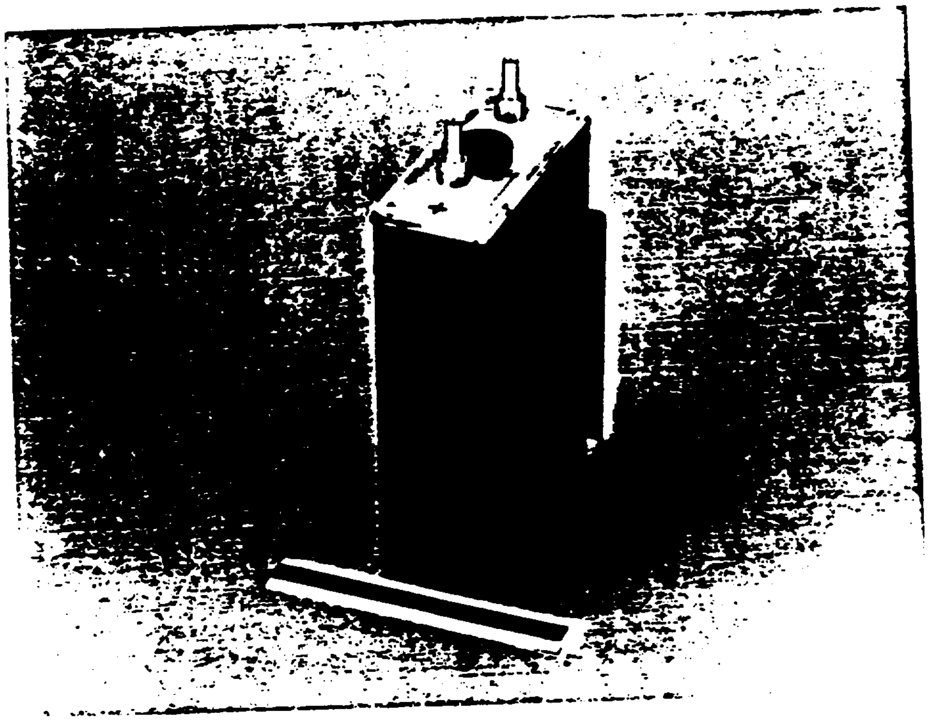


FIGURE 7. SINDORF

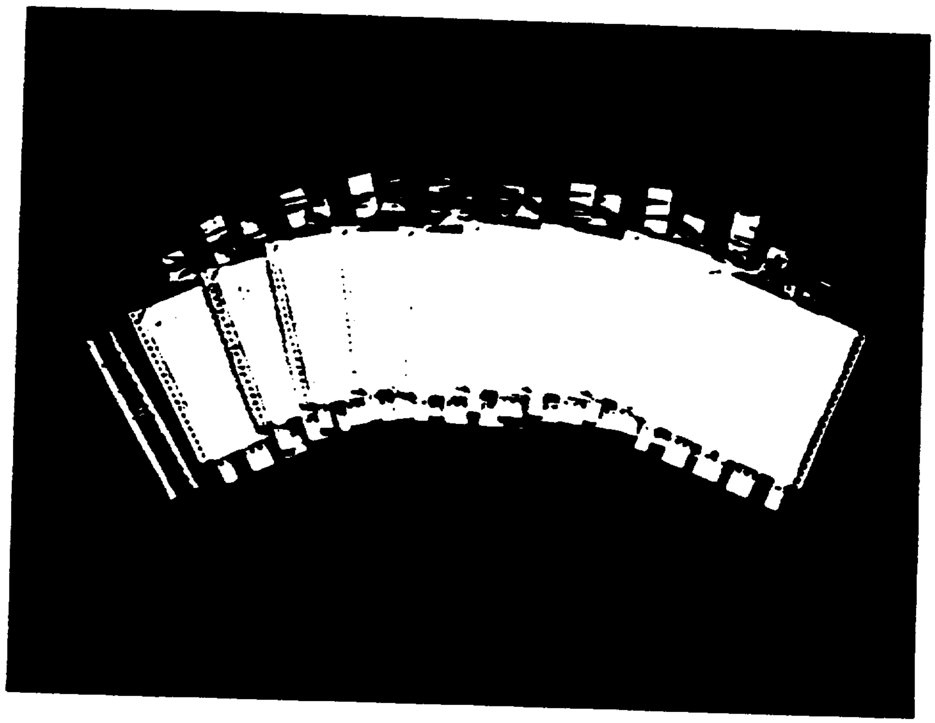


FIGURE 8. SINDORF

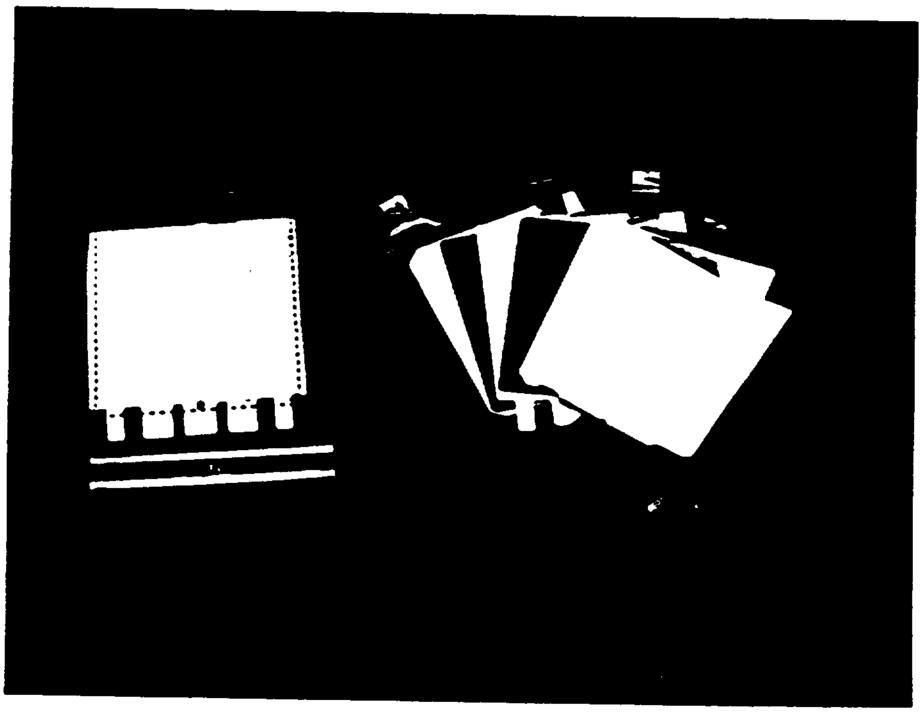


FIGURE 9. SINDORF

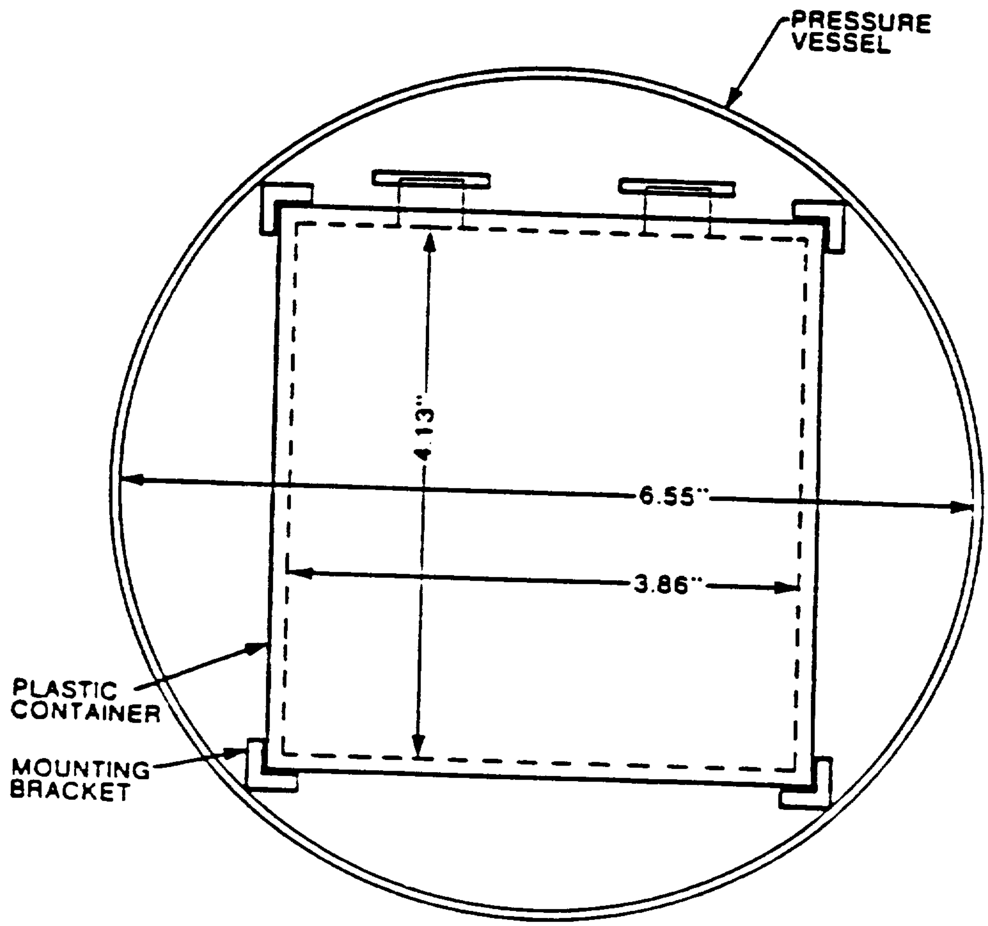


FIGURE 10. SINDORF

CELL COMPONENT THICKNESSES

COMPONENT	INTELSAT V Ni/Cd			CPV Ni/H_2		
	THICK-NESS (mils)	NO.	TOTAL (mils)	THICK-NESS (mils)	NO.	TOTAL (mils)
POSITIVE	30	13	390	30	13	390
NEGATIVE	30	14	420	6	13	78
SCREEN	--	--	--	10	13	130
SEPARATOR	10	13	130	15	13	195
CASE WALL	12	2	24	35	2	70
TOTAL THICKNESS			1,094			863

FIGURE 11. SINDORF

CELL COMPONENT WEIGHTS

CELL WEIGHTS AND TOTAL PERCENTAGE						
PARAMETER	INTELSAT V				CPV	
	Ni/H_2		Ni/Cd		Ni/H_2	
	(g)	(%)	(g)	(%)	(g)	(%)
POSITIVE ELECTRODE	330.0	37.0	341	32.6	322.0	53.5
NEGATIVE ELECTRODE	38.0	4.2	420	41.4	38.0	6.3
SEPARATORS	19.5	2.2	18	2.0	19.5	3.2
SCREENS	5.5	0.6	--	--	11.0	1.8
ELECTROLYTE	100.0	11.3	118	11.6	123.0	20.4
END PLATES	33.0	3.7	--	3.7	--	--
PRESSURE VESSEL	222.0	25.0	83	25.0	36.5	6.1
INTERNAL HARDWARE SEAL ASSY.	137.0	15.5	44	15.5	52.0	8.6
TOTAL	885.0	100.0	1,024	100.0	602.0	100.0

FIGURE 12. SINDORF

C-6.

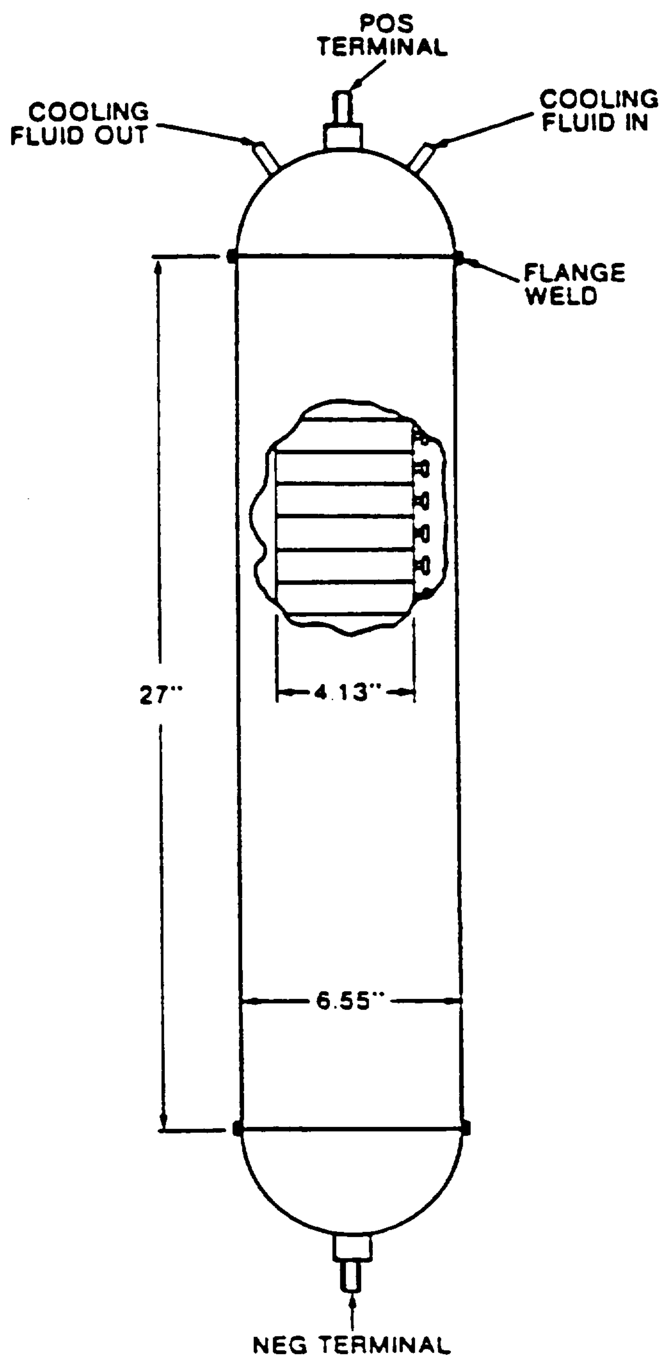


FIGURE 13. SINDORF

BATTERY COMPONENT WEIGHTS

BATTERY WEIGHTS AND TOTAL PERCENTAGE						
PARAMETER	INTELSAT V				CPV	
	Ni/H_2		Ni/Cd		Ni/H_2	
	(kg)	(%)	(kg)	(%)	(kg)	(%)
27 CELLS	23.90	81.0	28.70	88.5	16.25	74.1
CELL MOUNTING SHELLS	2.89	9.8	2.02	6.2	3.61	16.5
BASE PLATE	0.65	2.2	--	--	--	--
DIODE ASSY.	0.67	2.3	0.67	2.0	0.67	3.0
DIODE WIRING	0.19	0.6	0.19	0.6	0.19	0.9
STRAIN GUAGE ELECTRONICS	0.11	0.4	--	--	0.11	0.5
MISC. (wiring, insulation)	1.10	3.7	0.86	2.6	1.10	5.0
TOTAL WEIGHT	29.50	100.0	32.40	100.0	21.93	100.0

FIGURE 14. SINDORF

BATTERY CHARACTERISTICS

PARAMETER	INTELSAT V		CPV
	Ni/H_2	Ni/Cd	Ni/H_2
MEASURED CELL CAPACITY 10°C (Ah)	34.8	38.7	39.0
NUMBER OF CELLS IN BATTERY	27.0	28.0	27.0
STORED ENERGY PER BATTERY (Wh)	1,174.0	1,300.0	1,316.0
WEIGHT OF BATTERY (kg)	29.5	32.4	21.9
ENERGY/UNIT WEIGHT (Wh/kg)	39.8	40.1	60.0
VOLUME OF BATTERY (L)	59.9	13.3	18.2
ENERGY/UNIT VOLUME (Wh/L)	19.6	97.7	72.3

FIGURE 15. SINDORF

ADVANTAGES OF CPV Ni/H_2 BATTERIES

ITEM	IPV INTELSAT V	CPV SIZED TO INTELSAT V	COMPARISON
CELL WEIGHT (g)	885.0	602.0	32% LESS
BATTERY WEIGHT (kg)	29.5	21.9	26% LESS
ENERGY/UNIT WEIGHT (Wh/kg)	39.8	60.0	50% IMPROVEMENT
ENERGY/UNIT VOLUME (Wh/L)	19.6	72.3	270% IMPROVEMENT
COST ($/kWh)	25,000.0	1,710.0	15/1 REDUCTION

FIGURE 16. SINDORF

TERRESTRIAL CPV NI/H2 BATTERY

COST PROJECTIONS

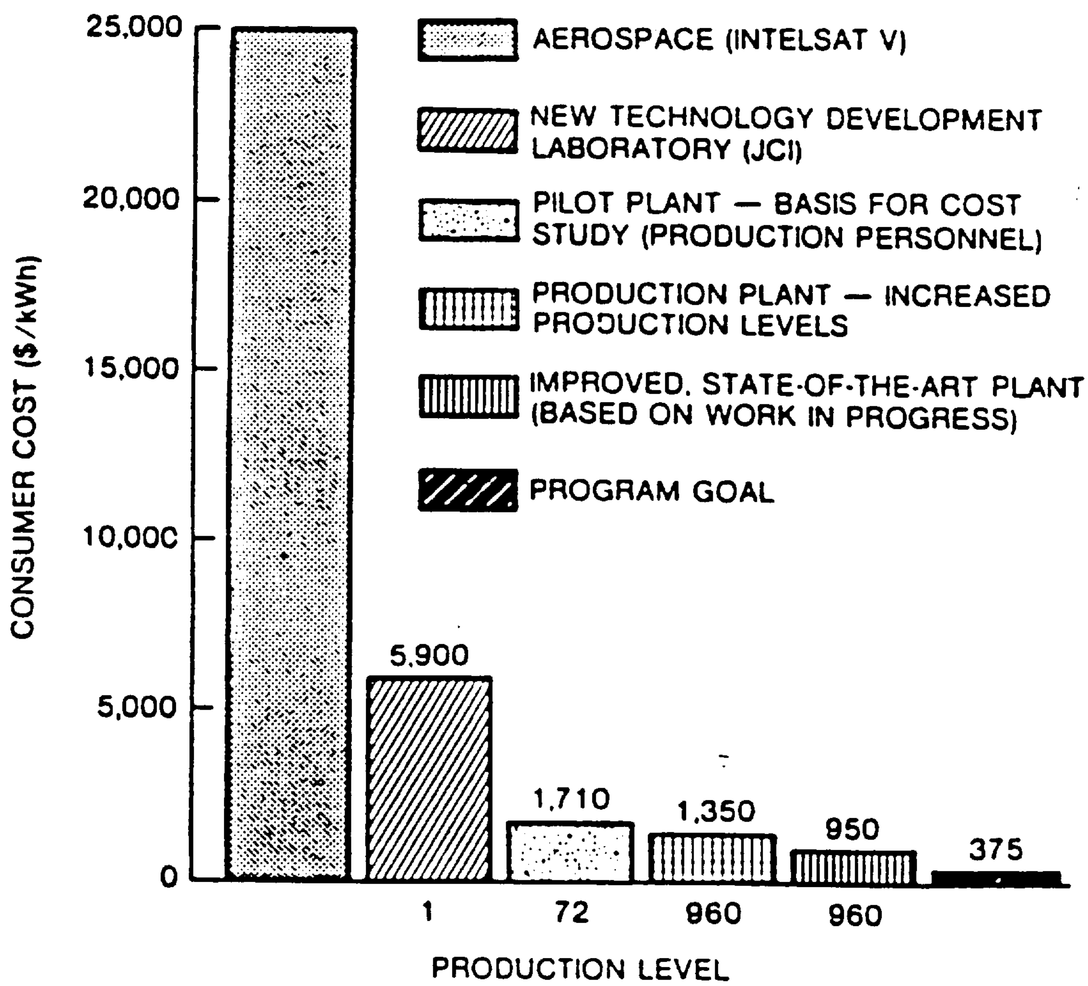


FIGURE 17. SINDORF

CONCLUSIONS

DEVELOPMENT OF

COMMON PRESSURE VESSEL DESIGN

OF NICKEL HYDROGEN

RECOMMENDED FOR AEROSPACE BATTERIES

POTENTIAL ADVANTAGES:

- -15 TO 1 REDUCTION IN COST
- -50% IMPROVEMENT IN ENERGY EFFICIENCY
- -3 TO 1 REDUCTION IN VOLUME

FIGURE 18. SINDORF

ACKNOWLEDGEMENTS

JIM DUNLOP

COMSAT

RICHARD BEAUCHAMP

JOHNSON CONTROLS

FIGURE 19. SINDORF

"RECENT DEVELOPMENTS IN NiH_2 TECHNOLOGY"

JOHN KENNEDY presented by ARNOLD HALL

Arnold Hall went on to give the talk originally to be given by John Kennedy on "Recent Developments in NiH_2 Technology at Whittaker-Yardney."

The four cells shown in (Hall [Figure 2]) are now on life tests, and others are also about to be tested by NASA. Life cycle voltage trends for MANTECH cells to over 10,000 cycles are show in (Hall [Figure 3]). In (Hall [Figure 4]), on NiH_2 Cell Life Cycle Testing, I = interrupted and C = continuous testing. Referring to (Hall [Figure 5]), it is noted that significant storage periods have not affected cell performance. Regarding the MANTECH cells, three of these are in test at Yardney; they been, in effect, reconditioned at every 1000 cycles during recharacterization. At ten thousand cycles the tests were interrupted for 10 months.

Cell expansion continues to be an issue. Growth of 1.9 mils/plate was found in the 50 amp-hour cells (Mantech) at 5000 cycles (Hall [Figure 6]). At 10000 cycles the growth rate decreased. No blisters were observed in cells BV to CP.

In studying the boiler-plate cells, (Hall [Figure 7]), it was found that plate capacity can be increased through additives--a 5 to 8 percent increase has been obtained.

Thicker Nickel electrodes (> 40 mils) are now being studied at Whittaker-Yardney (Hall [Figure 8]).

Q. Fuhr (Martin Marietta): What were the pressures on the stack before and after expansion?

A. Don't have them.

Q. Miller (Eagle-Picher): In the stress test do you discharge to a preselected DOD?

A. Yes. Stress tests had DOD of 80 to 95 percent.

Q. Willis (AT&T): Do you have a preferred method of cell storage?

A. We recommend storing in the shorted condition at 20 degrees C.

Q. Methlie (Government): Regarding the weight budget for the 3.5 and 4.5 inch cells, what is the proportion used by the case change? Why does the energy density go down in the larger cell?

A. It's a combination of things. Use of the inside volume effectively has to be the reason. I haven't got a solid reason.

Q. _____: Similar studies were done about ten years ago. The larger diameters shouldn't cause the decreased energy density. That wasn't found to be the situation ten years ago.

A. We need to look at this further.

At this point there was a lunch break with the session to resume starting with John Harvey's talk.

Whittaker

NICKEL HYDROGEN CELL TECHNOLOGY

AT

WHITTAKER - YARDNEY POWER SYSTEMS

NOVEMBER 1987

A PRESENTATION TO THE 1987 NASA/GSFC BATTERY WORKSHOP

FIGURE 1. KENNEDY

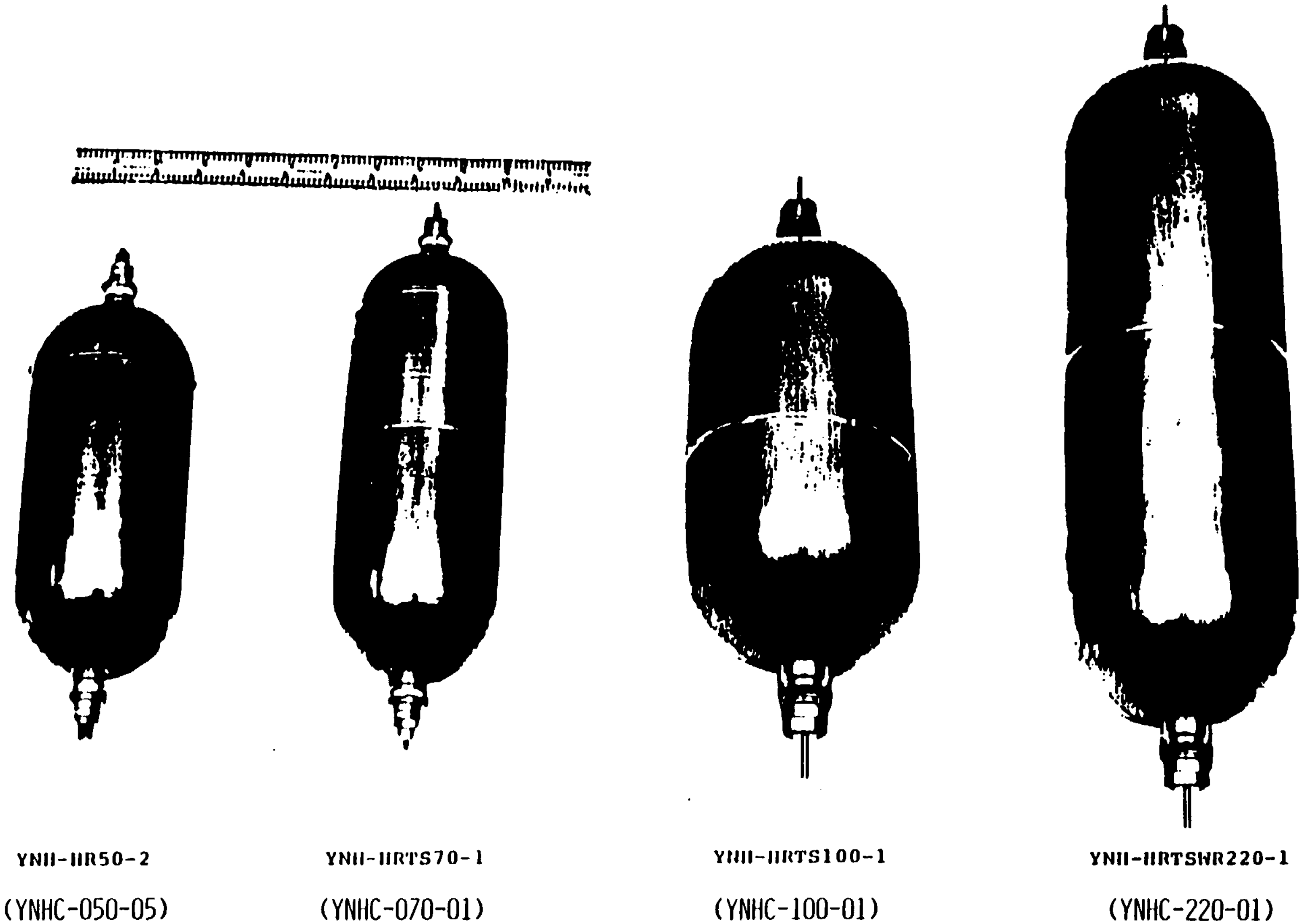


FIGURE 2. KENNEDY

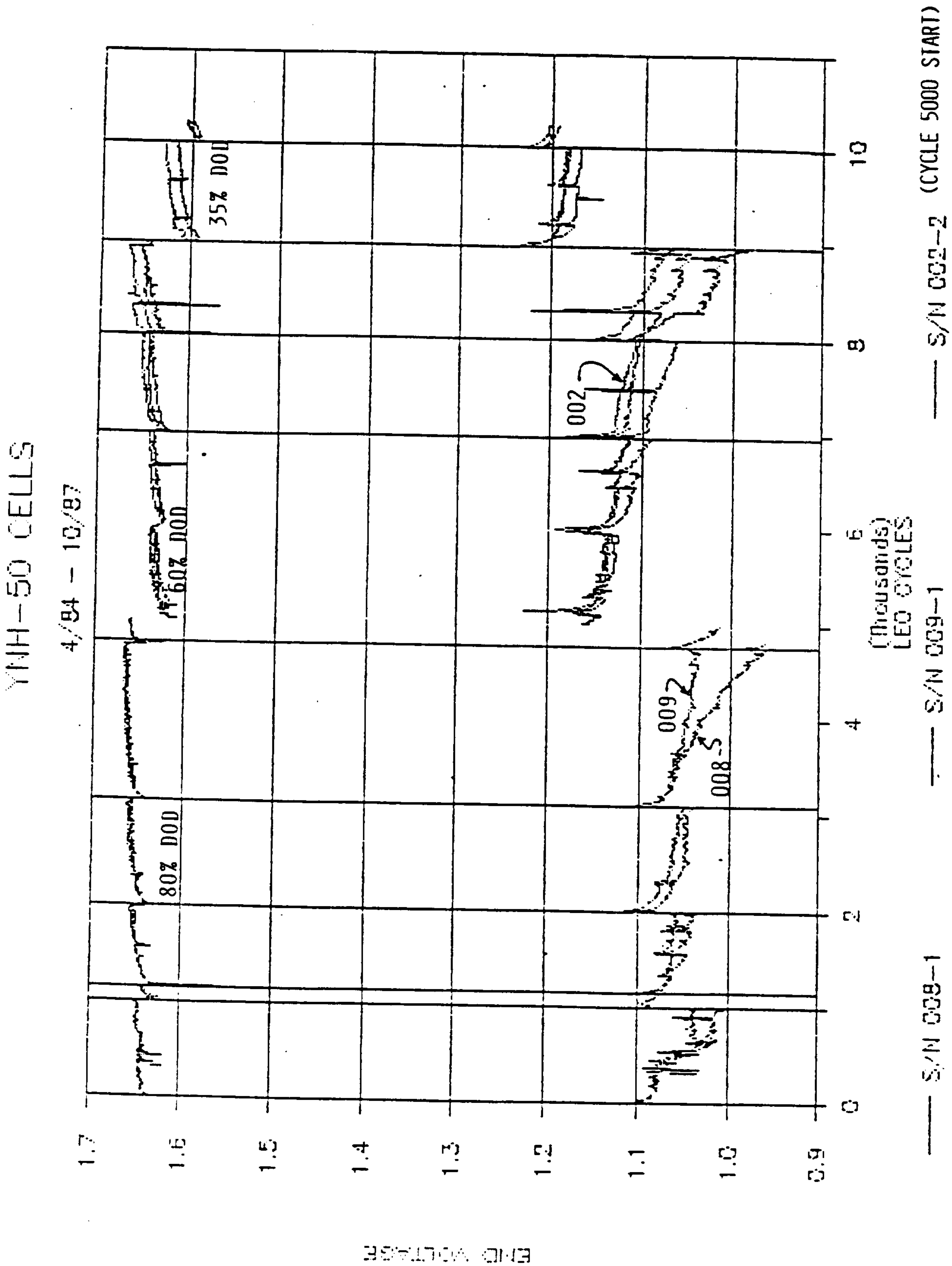


FIGURE 3. KENNEDY

Whittaker

NiH_2 CELL LIFE CYCLE TESTING

LOCATION	CELL TYPE	NO. UNITS	REGIME (TYPE/% DOD)	CURRENT STATUS	CONTIN/ INTERR. (MOS.)
WHITTAKER-YARDNEY	HR50 (MANTECH)	3	LEO/80, 60, 35	10250 + CYCLES	I (10)
WHITTAKER-YARDNEY/FORD	HRTSWR220	5	LEO/40	450 + CYCLES	I (17)
MARTIN MARIETTA	HR50 (MANTECH)	6	LEO/40	8520 + CYCLES	C
	HRTS100	4	LEO/40	1470 + CYCLES	C
NWSC-CRANE	HR50 (MANTECH)	10	LEO/40	3650 + CYCLES	C
		10	LEO/40	1450 + CYCLES	C
		10	LEO/60	890 + CYCLES	C
RCA	HRTS70	5	LEO/50	4200 + CYCLES	C
		5	LEO/30	5400 + CYCLES	C
NASA-LeRC	HR50 (MANTECH)	3	LEO/80, 60, 40, 10	6000 + CYCLES	I (12)

CURRENT AS OF OCTOBER 1987

FIGURE 4. KENNEDY

Whittaker

CELL CAPACITY VERSUS STORAGE

CELL TYPE	STATUS AT STORAGE START	STORAGE PERIOD (MOS.)	CAPACITY AT STORAGE END (1)	STORAGE CONDITION
50AH (MANTECH)	5000 CYCLES/45.9AH (2)	10	37.1AH (2) (1ST)	SHORTED
50AH (MANTECH)	10000 CYCLES/35.4AH (3)	10	38.8AH (3) (1ST)	VERTICAL, 20°C
50AH (MANTECH)	13 + CYCLES/53.3AH (4)	12	53AH (4)	SHORTED, 20°C
220AH (TANDEM)	160 CYCLES/259AH (5)	17	248AH (5) (3RD)	SHORTED, HORIZONTAL, 20°C

NOTES:

(1) CAPACITY AT POST-STORAGE CYCLE NOTED ( ).
(2) ONE PHASE 3 CELL
(3) AVG, TWO PHASE 2 CELLS
(4) AVG, THREE CELLS
(5) AVG, FIVE CELLS

FIGURE 5. KENNEDY

NICKEL ELECTRODE EXPANSION WITH CYCLING

IN-CELL DATA

CELL	NO. (+)	STACK EXPANSION @ 5000 CYCLES (1)	STACK EXPANSION @ 10000 CYCLES
50AH (MANTECH)	40	0.078 (.00195/PLATE, EQUIV.)	0.094 (.00235/PLATE EQUIV.)

STRESS TEST DATA

ELECTRODE BATCH IDENT.	DIAMETER (IN. NOM)	THICKNESS (MILS, NOM)	STRESS TEST CYCLES (2)	NO. TEST PLATES	Δ THICKNESS AVG./RANGE (MILS) (3)
AS	3.5	31	200	6	0.8/0.3-1.1
AU	3.5	31	200	2	1.4/1.0-1.9
BI	4.5	31	200	6	0.9/0.6-1.4
BO	3.5	31	200	10	1.8/0.4-2.5
BV	3.5	35	200	6	2.1/1.6-2.6
BY	4.5	31	200	6	1.0/0.5-1.5
CL	3.5	35	200	4	1.6/0.8-1.9
			400		2.4/2.1-2.8
CN	3.5	35	400	4	1.5/1.2-1.7
CP	4.5	35	200	4	1.3/1.1-1.5

NOTES:

(1) AVERAGE OF 2 CELLS (MEASURED VIA STACK REFERENCE POINTS IN X-RAY)

(2) STRESS TEST VIA STANDARDIZED 10C (APPROX.) CHARGE/DISCHARGE FOR 80 TO 95% DOD

(3) ACCEPTANCE CRITERION = 3 MILS MAXIMUM

FIGURE 6. KENNEDY

CELL CAPACITY ENHANCEMENT

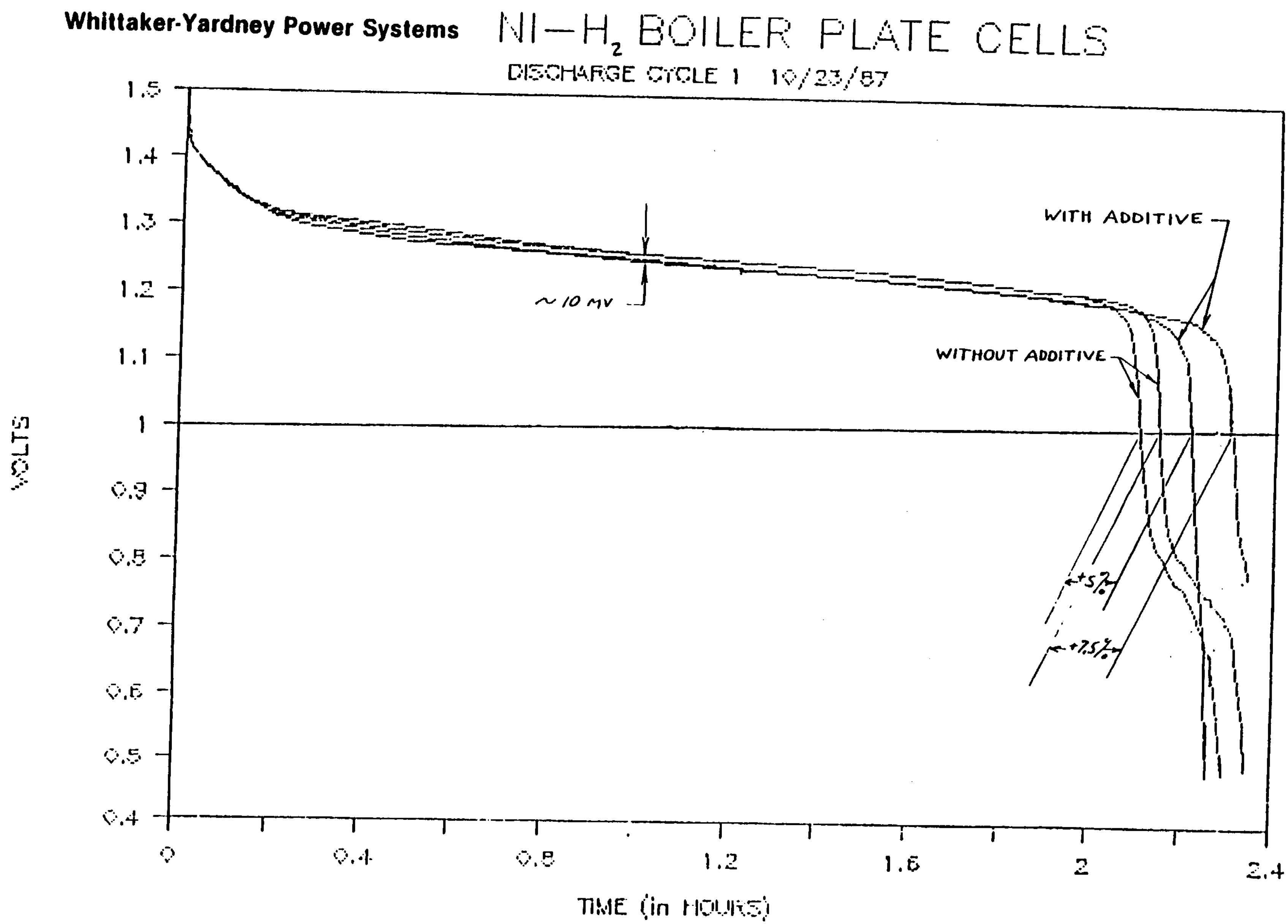


FIGURE 7. KENNEDY

Whittaker

CURRENT NiH_2 DEVELOPMENT ACTIVITIES AT WHITTAKER-YARDNEY

- o NICKEL ELECTRODE PERFORMANCE ENHANCEMENT
- o THICK NICKEL ELECTRODE DEVELOPMENT
- o CELL DESIGN OPTIMIZATION
- o CELL LIFE CYCLE & SPECIAL TESTING
- o COMPONENT & MANUFACTURING COST REDUCTION

FIGURE 8. KENNEDY

"RECENT PROGRESS IN NiH_2 CELL/BATTERY TECHNOLOGY"

JOHN SMITHRICK

John Smithrick (NASA LeRC) spoke on "Recent Progress in Ni H_2 Cell/Battery Technology at NASA Lewis Research Center." LeRC is investigating the IPV NiH_2 cell, the bipolar NiH_2 battery, and component development (Smithrick [Figure 2]). Some of the new features of the advanced cell are the use of floating stacks, serrated separators, and reduced KOH concentration. Varying KOH concentration has a significant effect on cycle life. The selection of 26 percent KOH is regarded as a breakthrough (Smithrick [Figures 6, 7 and 8]).

The Ni electrode is the greatest contributor to the weight of the cell, and the substrate is the greatest contributor to the weight of the electrode (Smithrick [Figures 18, 19, and 20]).

Q. Miller (Eagle-Picher): There was a question about the HST using NiH_2. We have now exceeded 33000 cycles at 15 percent DOD.

Q. Badcock (Aerospace Corp.) One out of seven Yardney cells showed a problem with storage. There can be a storage problem.

A. Okay

Q. Methlie (Government): What are the characteristics of the separators?

A. Potassium Titanate-Polyethylene has a thickness of about 10 mils and bubble pressure > 30 psi. Polyethylene is being considered as a zircar replacement.

A. Gonzalez-Sanabria (NASA LeRC): They have about 75 percent porosity, resistivity about 4 ohm-cm, 150 percent electrolyte retention. They basically meet the requirements reported two years ago at the IECEC conference.

POWER TECHNOLOGY DIVISION

Lewis Research Center

RECENT PROGRESS IN Ni/H_2 CELL/BATTERY TECHNOLOGY AT NASA LEWIS RESEARCH CENTER

BY

JOHN J. SMITHRICK

MICHELLE MANZO

OLGA D. GONZALEZ-SANABRIA

RANDALL F. GAHN

DORIS L. BRITTON

FOR PRESENTATION AT NASA GODDARD BATTERY WORKSHOP

NOVEMBER 4-5, 1987

FIGURE 1. SMITHRICK

NICKEL-HYDROGEN CELL/BATTERY TECHNOLOGY

GOAL

- IMPROVE CYCLE LIFE AND PERFORMANCE OF NICKEL-HYDROGEN BATTERIES

AREAS UNDER INVESTIGATION

- IPV CELL
  - EVALUATE SOA CELLS
  - ADVANCED IPV CELL DESIGNS
  - INVESTIGATE CAPACITY LOSS ON STORAGE
- BIPOLAR BATTERY
  - DEVELOPMENT OF OPTIMIZED BIPOLAR NICKEL-HYDROGEN BATTERY
  - DESIGN AND DEMONSTRATION OF A HIGH VOLTAGE BIPOLAR BATTERY CAPABLE OF PULSE OPERATIONS
- COMPONENT DEVELOPMENT
  - SEPARATOR
  - LIGHT WEIGHT NICKEL ELECTRODES

APPROACH

- LEWIS/INDUSTRY INTERACTIONS
  - CONTRACTS
  - IN-HOUSE

FIGURE 2 SMITHRICK

POWER TECHNOLOGY DIVISION

Lewis Research Center

SOA CELL

OBJECTIVE

- EVALUATE SOA SPACE WEIGHT IPV NICKEL-HYDROGEN CELLS

APPROACH

- EFFECT OF STORAGE
- EFFECT OF CHARGE/DISCHARGE CYCLING

STATUS

- COMPLETED STORAGE AND CYCLE TEST AT DEEP DEPTHS OF DISCHARGE (80, 60 AND 40%) ON YARDNEY MANTECH 50Ah IPV Ni/H_2 CELLS
- CYCLE TEST OF MANTECH CELLS AT 10% DOD IN PROGRESS
- CELLS ON ORDER FROM YARDNEY, EAGLE PICHER, AND HUGHES

FIGURE 3. SMITHRICK

SOA CELL

EFFECT OF STORAGE ON CAPACITY OF 50 AH YARDNEY SPACE WEIGHT IPV Ni/H_2 CELLS

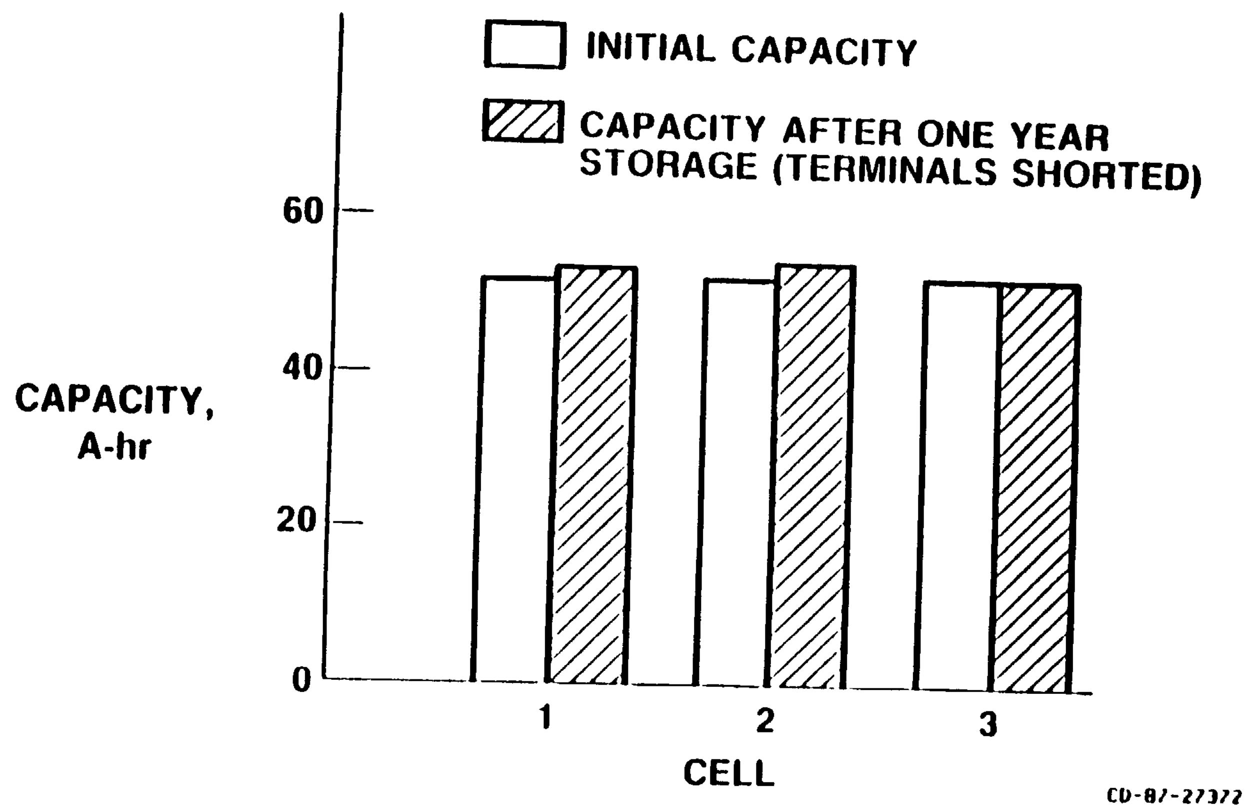


FIGURE 4. SMITHRICK

SOA CELL

CYCLE TEST 10% DOD - YARDNEY MANTECH 50Ah Ni/H_2 CELLS

BACKGROUND

- IPV Ni/H_2 BATTERY BEING CONSIDERED AS ALTERNATE FOR HUBBLE SPACE TELESCOPE
- FOR THIS APPLICATION 10% DOD WITH OCCASIONAL DEEPER DOD (40%)
- CYCLE LIFE OF Ni/H_2 BATTERY AT SHALLOW DOD PROJECTED TO BE ADEQUATE BUT LIMITED DATA BASE INADEQUATE FOR VERIFICATION
- AT SHALLOW DEPTH OF DISCHARGE CHARGE EFFICIENCY DECREASE COULD INFLUENCE DIVERGENCE IN CELL VOLTAGE
- CYCLE HISTORY OF CELLS PRIOR TO 10% DOD, ON THE TEST
  - CUMULATIVE CYCLES AT 80, 60, AND 40% DOD, ON THE AVERAGE FOR 3 CELLS WAS 4689 CYCLES

RESULTS

- CELLS HAVE BEEN CYCLED FOR OVER 1100 CYCLES WITH NO SIGNIFICANT SPREAD IN END OF DISCHARGE VOLTAGE

FIGURE 5. SMITHRICK

POWER TECHNOLOGY DIVISION

NASA Lewis Research Center

ADVANCED CELL DESIGN

OBJECTIVE

- IMPROVE CYCLE LIFE OF IPV Ni/H_2 CELL

APPROACH

- REVIEW SOA CELL DESIGN AND TEST DATA TO IDENTIFY FAILURE MODES
- MODIFY DESIGN TO ELIMINATE FAILURE MODES
- MODIFY NICKEL ELECTRODE ENVIRONMENT - 26% KOH
- VERIFICATION TEST

STATUS

- DEMONSTRATED FEASIBILITY OF DESIGN IN BOILER PLATE CELLS
- VERIFY IN FLIGHT WEIGHT CELLS
- ROLLOVER IMPROVED DESIGN CELL TO INDUSTRY

FIGURE 6. SMITHRICK

POWER TECHNOLOGY DIVISION

NASA Lewis Research Center

ENGINEERING AND CHEMICAL ADVANCES

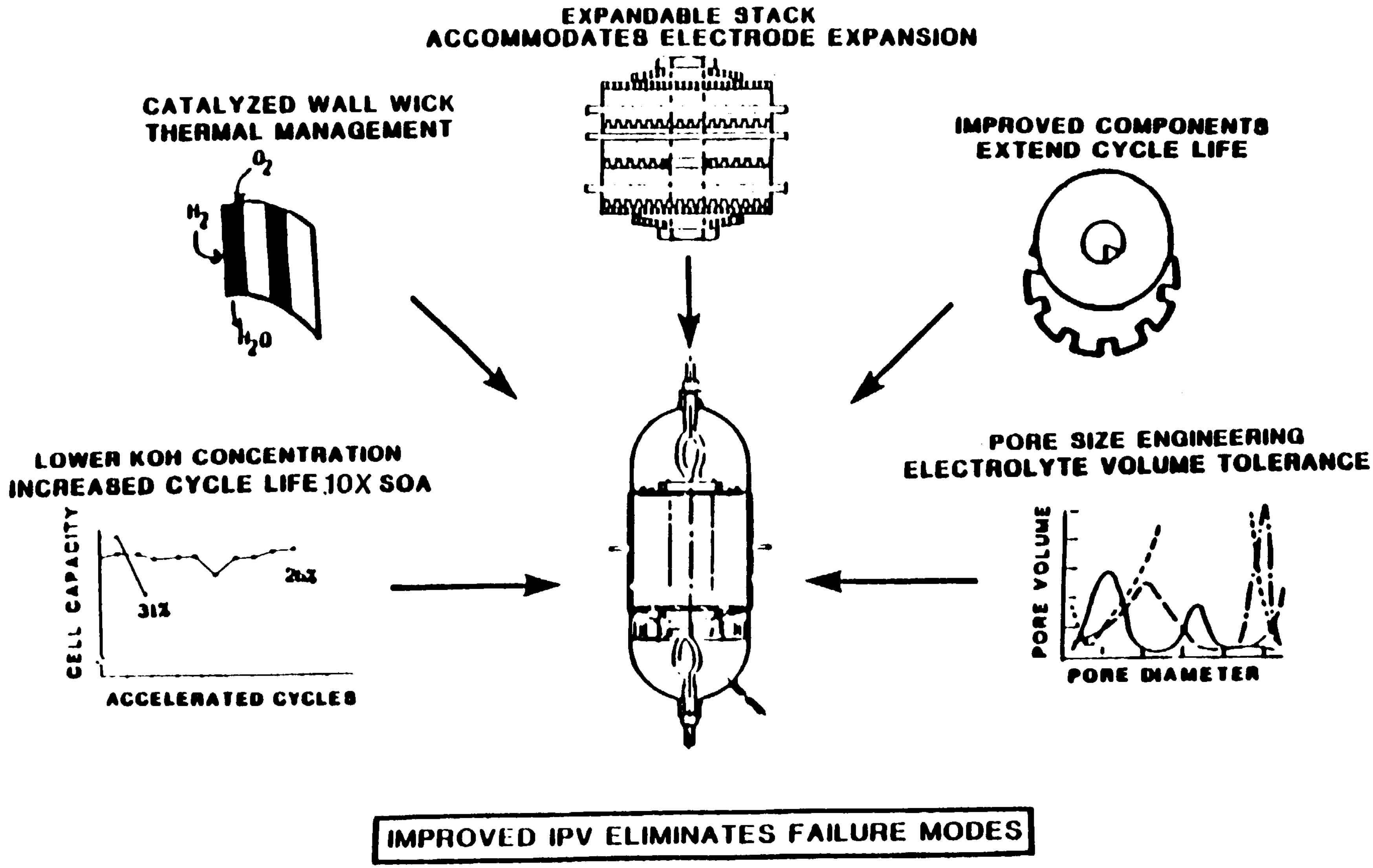


FIGURE 7. SMITHRICK

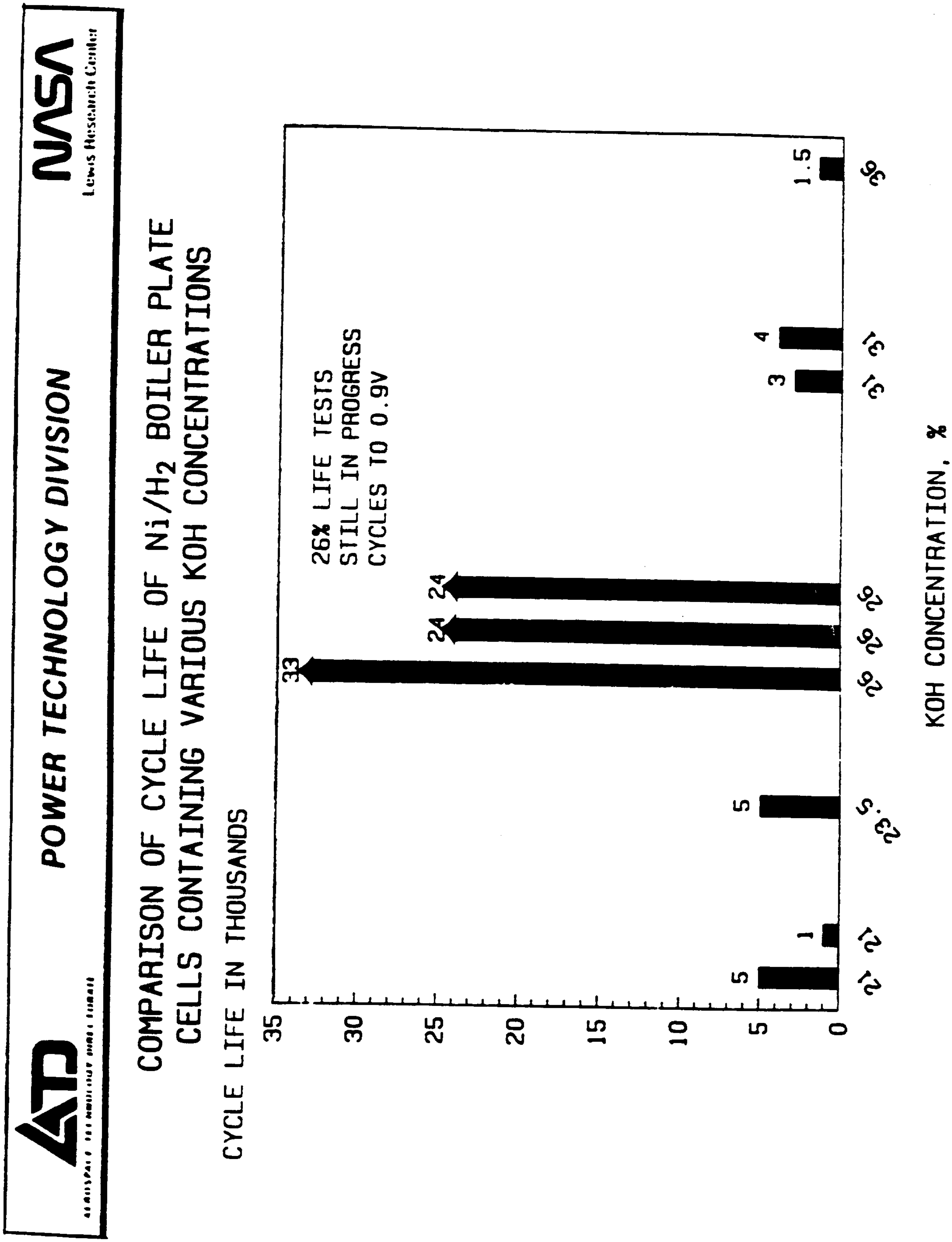


FIGURE 8. SMITHRICK

POWER TECHNOLOGY DIVISION

Lewis Research Center

ADVANCED CELL COMPRESSION TEST

OBJECTIVE

- INVESTIGATE EFFECT OF STACK COMPRESSION ON CELL PERFORMANCE

APPROACH

- BOILER PLATE PRESSURE VESSEL MODIFIED BY ADDITION OF MECHANICAL FEEDTHROUGH ON BOTTOM OF VESSEL TO PERMIT DIFFERENT COMPRESSIONS TO BE APPLIED TO THE STACK COMPONENTS
- COMPRESSION LOADING FROM 0.94 TO 46.3 PSI APPLIED BY SUSPENDING WEIGHTS FROM FEEDTHROUGH ROD
- CELL CHARGE AND DISCHARGE VOLTAGE MONITORED AT DIFFERENT LOADING

STATUS

- COMPRESSION TEST COMPLETED

RESULTS

- LESS THAN 10mV CHANGE IN VOLTAGE ON CHARGE OR DISCHARGE DUE TO VARYING COMPRESSION FROM 0.94 TO 46.3 PSI

FIGURE 9. SMITHRICK

IPV NICKEL-HYDROGEN CELL COMPRESSION-TEST FACILITY

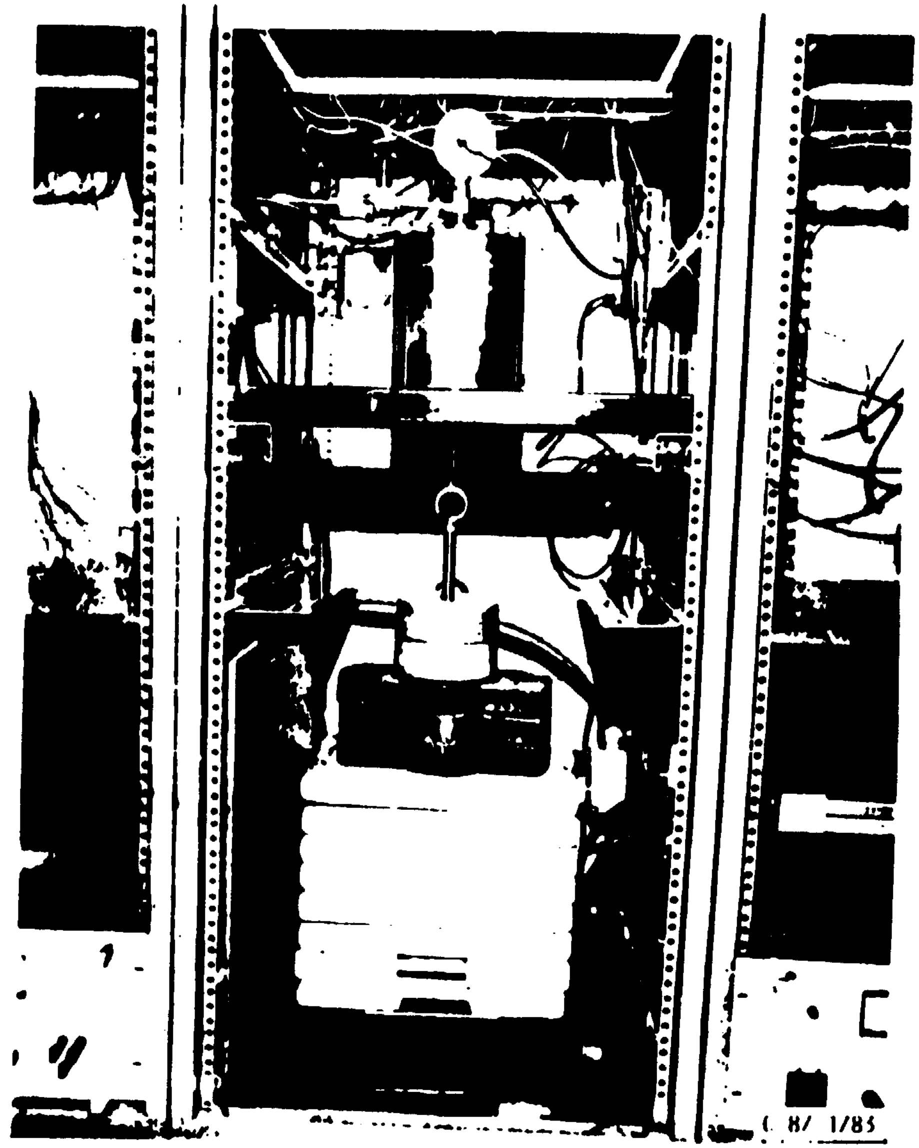


FIGURE 10. SMITHRICK

ADVANCED CELL

LIGHTWEIGHT IPV NICKEL-HYDROGEN CELL PARAMETRIC STUDY

OBJECTIVE

- DETERMINE THE EFFECTS OF COMPONENT AND DESIGN VARIATIONS ON CELL SPECIFIC ENERGY AND ENERGY DENSITY

APPROACH

- DEVELOP COMPUTER PROGRAM TO CALCULATE CELL SPECIFIC ENERGY

  VARY THE FOLLOWING PARAMETERS:
  - NICKEL ELECTRODE
    - THICKNESS
    - POROSITY
    - LOADING
    - SUBSTRATE
  - SEPARATOR
    - TYPE - ASBESTOS, ZIRCAR, DEVELOPMENTAL
    - THICKNESS
  - CELL DESIGN
  - BACK-TO-BACK
  - RECIRCULATING
  - OPERATING PRESSURE
  - ELECTROLYTE CONCENTRATION
  - LIGHTWEIGHT CURRENT COLLECTORS FOR LOW DOD'S

STATUS

- COMPUTER PROGRAM COMPLETED
- PARAMETRIC STUDY INITIATED

FIGURE 11. SMITHRICK

POWER TECHNOLOGY DIVISION

Lewis Research Center

BIPOLAR BATTERY

OBJECTIVE

- DEVELOP AND DEMONSTRATE AN OPTIMIZED BIPOLAR NICKEL-HYDROGEN BATTERY WITH IMPROVED SPECIFIC ENERGY AND ENERGY DENSITY OVER STATE-OF-THE-ART TECHNOLOGY

APPROACH

- PARALLEL IN-HOUSE AND CONTRACTOR EFFORTS TO DESIGN AN OPTIMUM BATTERY FOR HIGH VOLTAGE, HIGH POWER, AND PULSE APPLICATIONS
- INCORPORATE IMPROVED AND LIGHTWEIGHT COMPONENTS FROM COMPONENT DEVELOPMENT PROGRAM
- DEMONSTRATE BIPOLAR TECHNOLOGY IN BOILER PLATE HARDWARE
- DESIGN FLIGHT WEIGHT, HIGH VOLTAGE PULSE BATTERY
- DEMONSTRATE PERFORMANCE OF OPTIMIZED BATTERY IN FLIGHT HARDWARE

FIGURE 12. SMITHRICK

ATD AEROSPACE TECHNOLOGY DIRECTORATE

POWER TECHNOLOGY DIVISION

NASA
Lewis Research Center

BIPOLAR BATTERY STATUS

IN-HOUSE PROGRAM

- BIPOLAR PERFORMANCE HAS BEEN DEMONSTRATED IN STACKS HAVING 5 TO 50 CELLS AND CAPACITIES RANGING FROM 1 TO 40 AH
- 10,000, 40% DOD LEO CYCLES HAVE BEEN ACHIEVED ON A 40 AH, 10 CELL BIPOLAR STACK WITH ACTIVE COOLING
- HIGH VOLTAGE PERFORMANCE WAS DEMONSTRATED IN A 50 CELL, 65 VOLT STACK THAT OPERATED 1500 CYCLES AT 40% DOD AND DEMONSTRATED PULSE CAPABILITY AT THE 5 C RATE
- A PASSIVELY COOLED, HIGH VOLTAGE STACK SPECIFICALLY FOR PULSE APPLICATIONS IS PRESENTLY BEING DESIGNED

FORD/YARDNEY CONTRACT

- BIPOLAR PERFORMANCE HAS BEEN DEMONSTRATED IN 10 CELL STACKS HAVING 12 TO 75 AH CAPACITIES
- THE SECOND 75 AH ACTIVELY COOLED BIPOLAR STACK HAS BEEN SUCCESSFULLY CHARACTERIZED AND IS PRESENTLY UNDERGOING LEO CYCLING AT 40% DOD
- PRESENT CONTRACT EFFORTS ARE BEING DIRECTED TOWARD CONSTRUCTION OF A 28 VOLT, ACTIVELY COOLED BIPOLAR STACK WITH PULSE CAPABILITIES

FIGURE 13. SMITHRICK

POWER TECHNOLOGY DIVISION

NASA Lewis Research Center

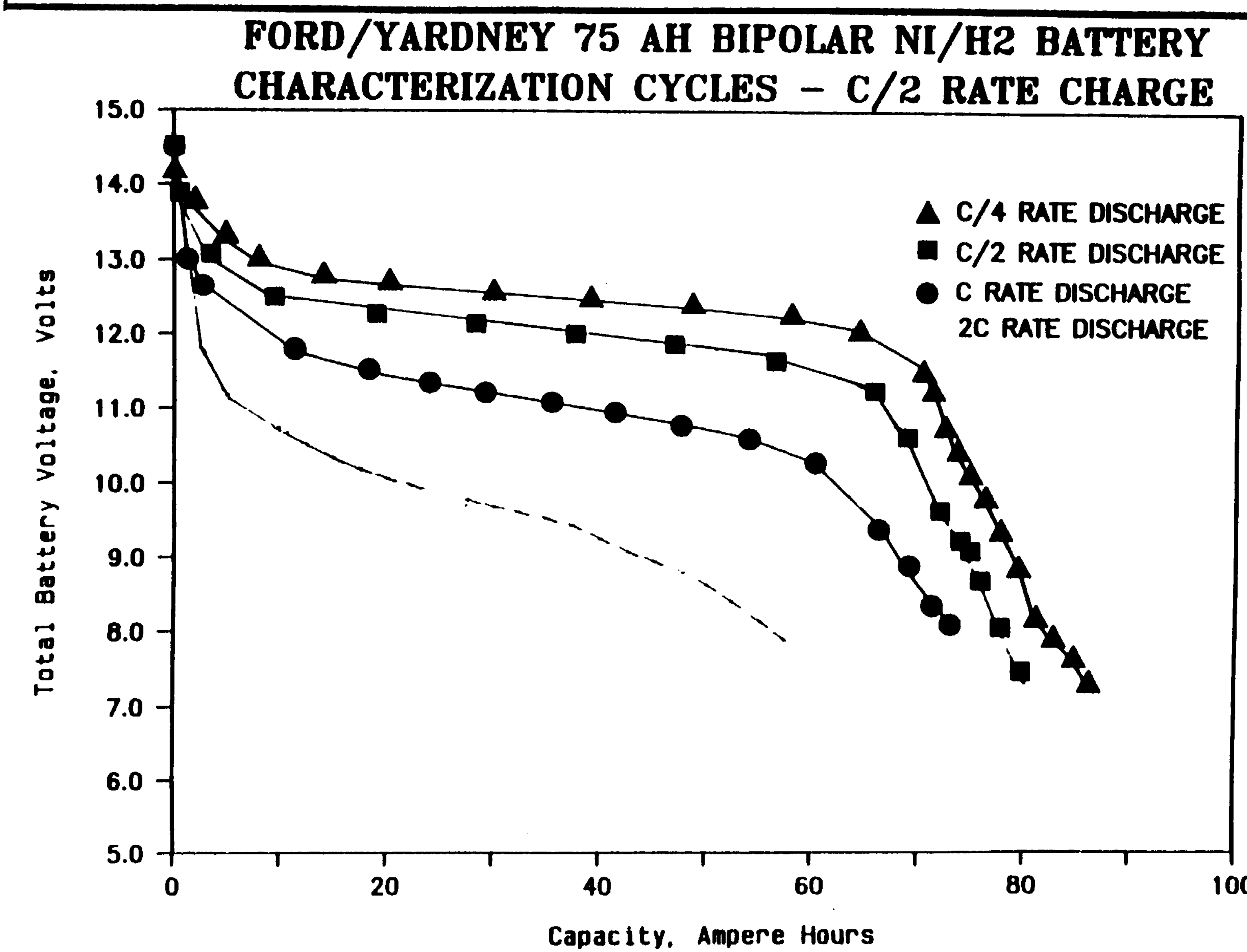


FIGURE 14, SMITHRICK

50 Cell Bipolar Ni/H2 Battery
5C Rate Pulse Test

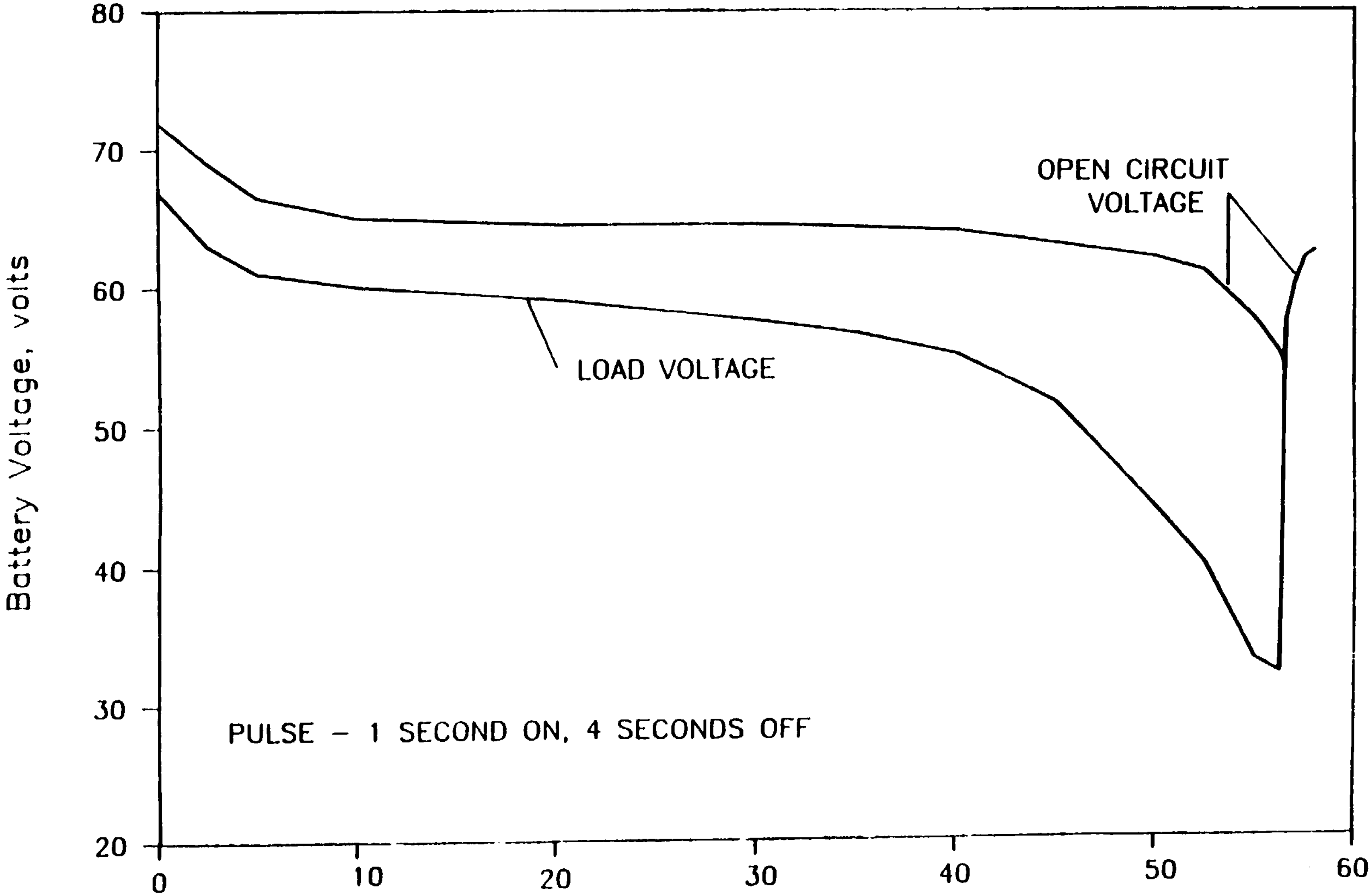


FIGURE 15. SMITHRICK

AEROSPACE TECHNOLOGY DIRECTORATE

POWER TECHNOLOGY DIVISION

NASA
Lewis Research Center

SEPARATOR DEVELOPMENT

OBJECTIVE

- DEVELOP A REPLACEMENT MATERIAL FOR ASBESTOS AND ZIRCAR SEPARATORS WHICH WILL BE OF EQUAL OR BETTER PERFORMANCE

BACKGROUND

- SEPARATOR CRITICAL RISK COMPONENT DUE TO QUESTIONABLE AVAILABILITY OF HIGH QUALITY ASBESTOS
- HIGH BUBBLE PRESSURE MATERIAL DESIRABLE
  - OXYGEN MANAGEMENT IN ADVANCED DESIGN CELLS
  - ELECTROLYTE MANAGEMENT
- LOW BUBBLE PRESSURE MATERIAL CAN BE ALTERNATIVE TO ZIRCAR
  - LOWER COST
  - BETTER HANDLING

FIGURE 16. SMITHRICK

POWER TECHNOLOGY DIVISION

NASA Lewis Research Center

SEPARATOR DEVELOPMENT

APPROACH

- IN-HOUSE DEVELOPMENT AND TESTING OF CANDIDATE SEPARATORS
- GRANT EFFORT WITH MIAMI UNIVERSITY OF OHIO TO DEMONSTRATE FEASIBILITY OF MAKING SEPARATORS USING STANDARD PAPER MAKING TECHNIQUES

STATUS

- SEPARATORS WITH DESIRABLE CHARACTERISTICS HAVE BEEN PRODUCED USING STANDARD PAPER TECHNOLOGY
  - POTASSIUM TITANATE - POLYETHYLENE AS ASBESTOS REPLACEMENT
  - POLYETHYLENE AS ZIRCAR REPLACEMENT
  - RADIATION GRAFTED POLYETHYLENE - ZIRCAR - DUAL SEPARATOR
- CHARACTERIZATION AND CYCLE TESTING IN BOILER PLATE CELLS IN PROGRESS
- CYCLE LIFE TESTING OF BEST SEPARATORS IN FLIGHT WEIGHT CELLS PLANNED
- SEPARATORS WILL BE AVAILABLE THROUGH NASA LeRC FOR INDUSTRY VERIFICATION
- ROLL OVER MANUFACTURING TECHNOLOGY TO INDUSTRY

FIGURE 17. SMITHRICK

POWER TECHNOLOGY DIVISION

Lewis Research Center

LIGHT WEIGHT ELECTRODE

OBJECTIVE

- REDUCTION OF BATTERY WEIGHT BY USE OF LIGHT WEIGHT SUBSTRATES

ALTERNATE SUBSTRATES

- SORAPEC
- NIPPON SEISEN
- FIBREX
- GRAPHITE
- PLASTIC

FIGURE 18. SMITHRICK

POWER TECHNOLOGY DIVISION

LIGHT WEIGHT NICKEL ELECTRODE

EFFECT OF LIGHT WEIGHT NICKEL ELECTRODES ON WEIGHT OF A 125 Ah BIPOLAR NICKEL-HYDROGEN BATTERY

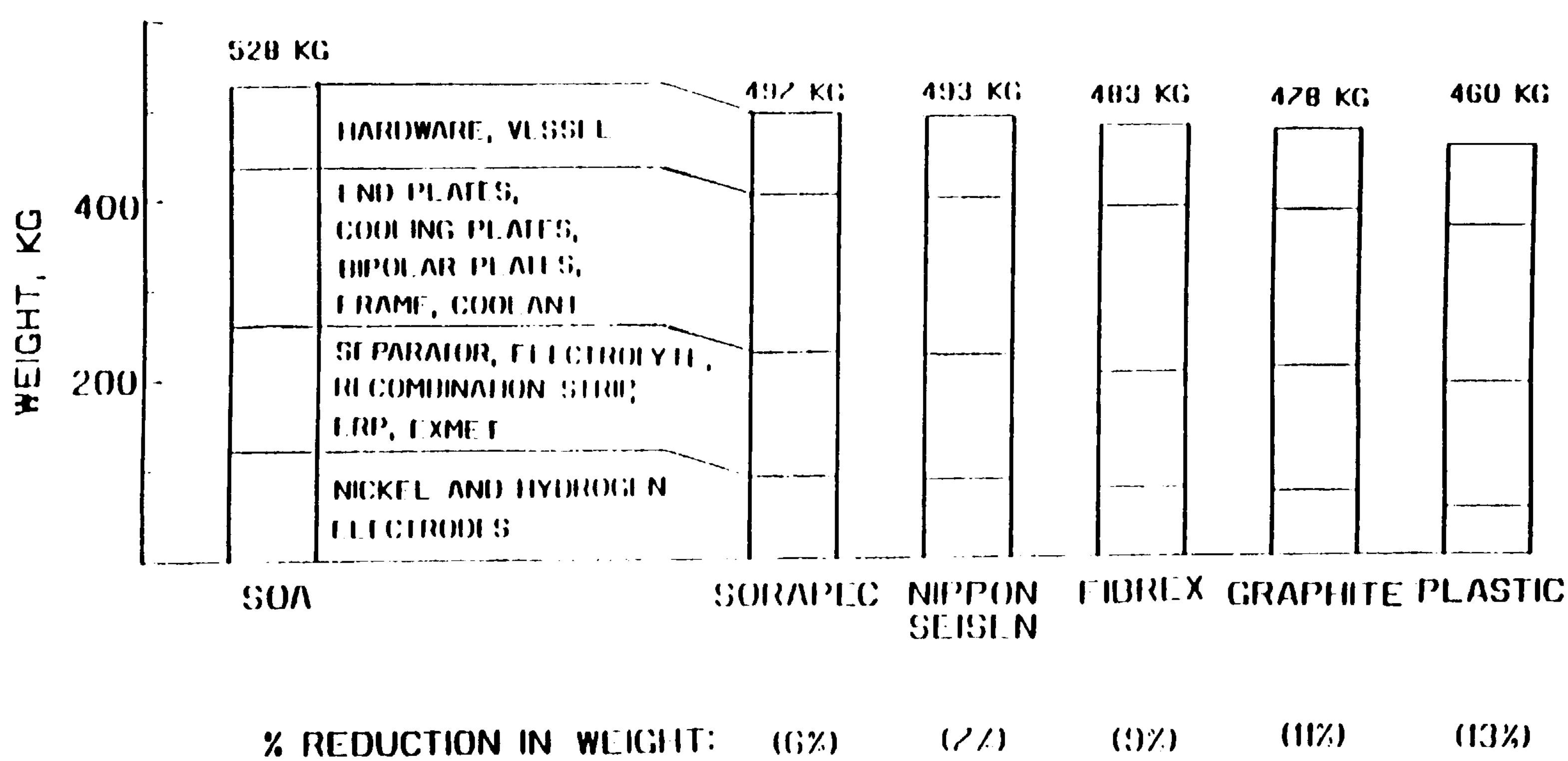


FIGURE 19. SMITHRICK

POWER TECHNOLOGY DIVISION

NASA Lewis Research Center

LIGHT WEIGHT ELECTRODE
EFFECT OF CYCLING ON UTILIZATION OF FIBREX ELECTRODE

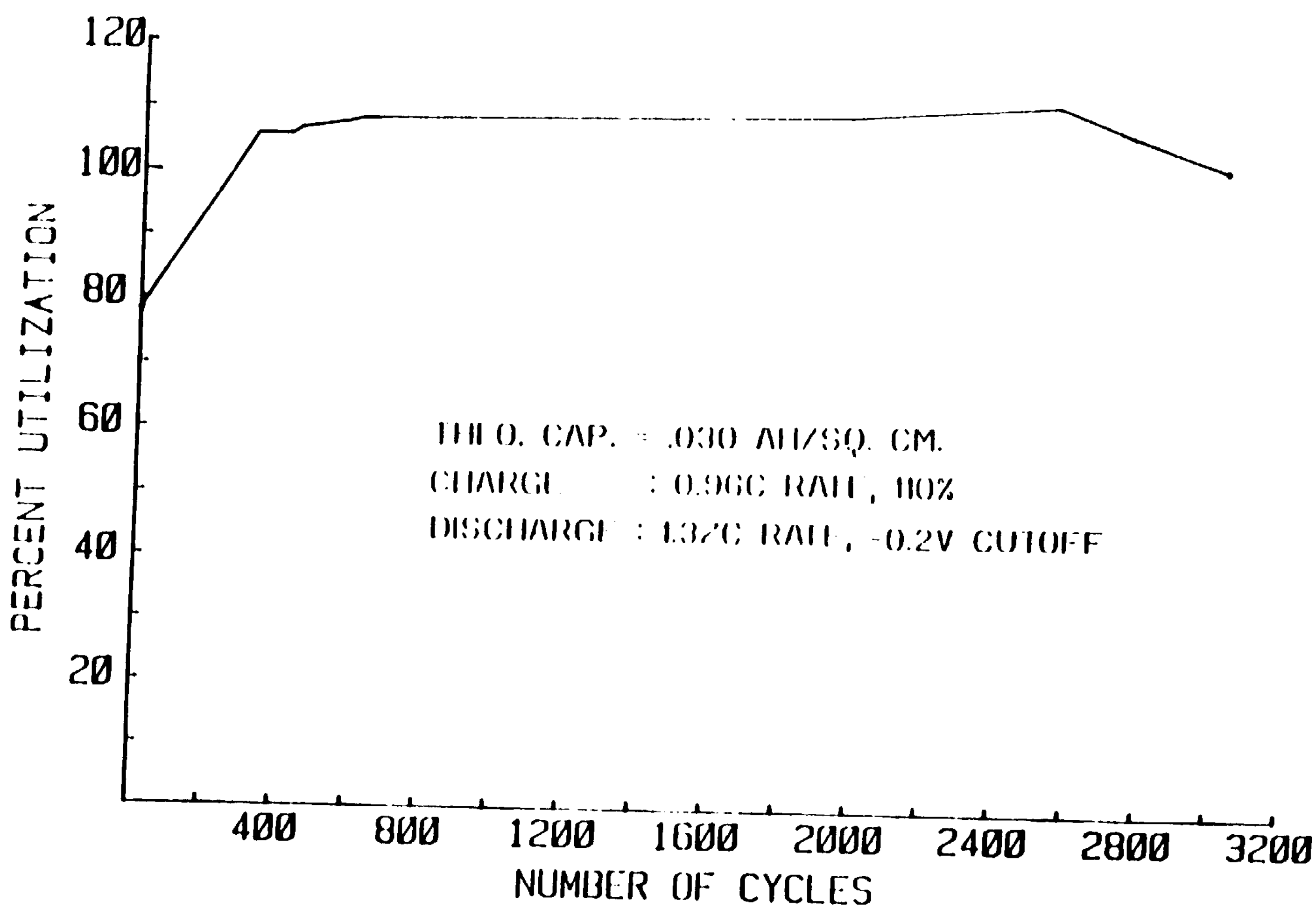


FIGURE 20. SMITHRICK

CONCLUDING REMARKS

STATE OF ART CELLS

- YARDNEY MANTECH CELLS
  - NO CAPACITY LOSS DUE TO ONE YEAR STORAGE
  - CYCLE TEST COMPLETED AT DEEP DEPTHS OF DISCHARGE
  - CYCLE TEST CONTINUING AT 10% DoD
- OTHER MANUFACTURERS
  - FLIGHT WEIGHT CELLS ON ORDER WILL BE EVALUATED

ADVANCE CELL

- DEMONSTRATED IN BOILER PLATE CELLS
- BREAKTHROUGH IN CYCLE LIFE-26% KOH, OVER 35,000 LEO CYCLES AT 80% DoD
- COMPRESSION TEST COMPLETED-INITIAL PERFORMANCE INDEPENDENT OF COMPRESSION
- LIGHT WEIGHT CELL-PARAMETRIC STUDY INITIATED ON EFFECT OF COMPONENT AND DESIGN VARIATIONS ON SPECIFIC ENERGY

BIPOLAR BATTERY

- DEMONSTRATED CYCLE PERFORMANCE IN BOILER PLATE CELLS
- DEMONSTRATED HIGH VOLTAGE AND PULSE DISCHARGE PERFORMANCE
- DESIGN AND DEMONSTRATE OPTIMUM FLIGHT WEIGHT BATTERY

COMPONENT DEVELOPMENT

- SEPARATOR
  - ALTERNATE SEPARATORS FOR ASBESTOS AND ZIRCAR PRODUCED USING STANDARD PAPER TECHNOLOGY
  - CYCLE TESTING IN BOILER PLATE CELLS IN PROGRESS
- LIGHT WEIGHT NICKEL ELECTRODE
  - CONTRACT-HUGHES RESEARCH INITIATED
  - INHOUSE-ELECTRODES BEING EVALUATED

FIGURE 21. SMITHRICK

"EFFECT OF KOH CONCENTRATION ON NiH_2 CELL PERFORMANCE"

HONG LIM

The final scheduled speaker was Hong Lim (Hughes Research Lab) on "Effect of KOH Concentration on NiH_2 Cell Performance."

A very important conclusion is that cycle life is very dependent on KOH concentration (Lim [Figure 2]).

In the boiler-plate cells the electrolyte sits at the bottom of the container. The wetness of the boiler-plate stack is comparable to the wetness of the flight cell stack. In the various curves of KOH concentration effects the hydrogen electrode of one cell was not properly connected and it is regarded as an anomaly cell. Changes in the charge/discharge ratio affect the relation between capacity and the KOH concentration effect. At very high discharge rates nonlinear behavior sets in. As shown in (Lim [Figure 17]), when the concentration of KOH is 26 percent, the capacity does not decrease as the number of cycles increases. There is a drastic dependence of cycle life on KOH concentration, with maximum cycle life at 26 percent KOH! The use of 45-minute cycles represents an accelerated life test as compared to the 90 minutes that would be encountered in an actual LEO flight.

Q. Chang (Ford Aerospace): What was the temperature during the cycle tests? Do you plan to test at different temperatures?

A. We don't plan to test at different temperatures. 23 degrees C has been the controlled outside temperature and 25 degrees C has been the maximum inside the cell temperature.

Q. Thierfelder (GE Astro): I note that 0.9 V was the criterion for failure. Suppose you had used 1.1 V--the more common requirement?

A. The difference is arbitrary. We used 0.9V because we had a 45 minute cycle regime.

Q. Chang (Ford Aerospace): Will you run - 10 degrees C, 0 degrees C for some of the tests?

A. No, we don't plan to do this.

KOH CONCENTRATION EFFECT ON THE CYCLE LIFE OF NICKEL-HYDROGEN CELLS

H. S. LIM AND S. A. VERZWYVELT

HUGHES RESEARCH LABORATORIES
MALIBU, CALIFORNIA 90265

SUPPORTED BY NASA-LEWIS (CONTRACT NO. NAS 3-22238)
(PROJECT ENGINEER: JOHN J. SMITHRICK)

HUGHES
AIRCRAFT COMPANY

FIGURE 1. LIM

CYCLE LIFE OF Ni/H_2 CELLS vs KOH CONCENTRATIONS

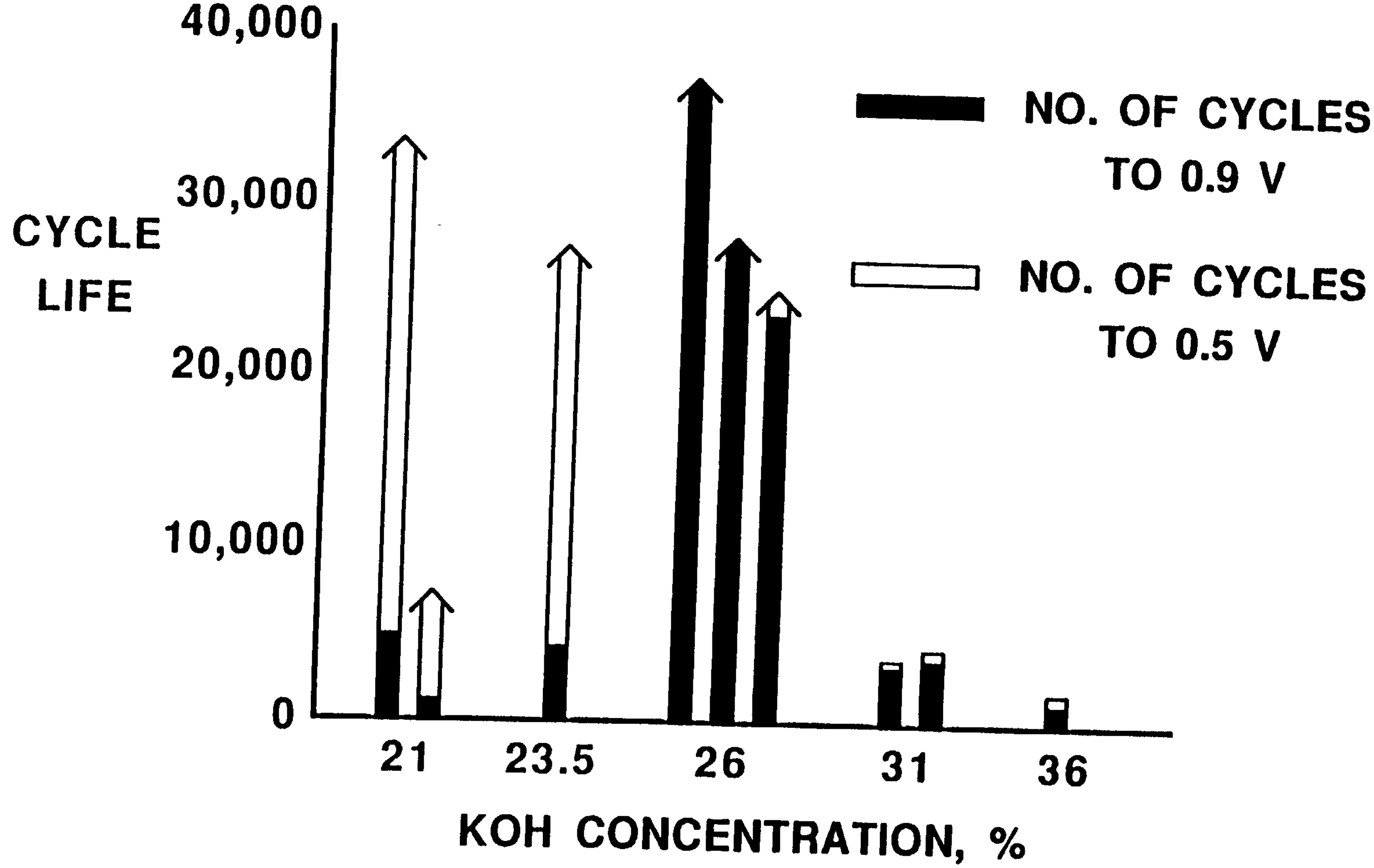


FIGURE 2. LIM

PROGRAM OUTLINE

HUGHES

- FABRICATE TEN Ni/H_2 BOILER PLATE CELLS (6.24 AH)
  - SIX NICKEL ELECTRODES
  - RECIRCULATION STACK DESIGN
  - ELECTROLYTE: 21 % TO 36 % KOH
- INITIAL CHARACTERIZATION TEST
  - CAPACITY AT VARIOUS CHARGE AND DISCHARGE RATES
- CYCLE LIFE TEST
  - 45 min LEO REGIME: 80 % DOD, C/D = 1.1
  - MONITORED: EODV, EOCV, EODP, EOCP
  - CAPACITY MEASUREMENTS: EVERY 1500 CYCLES
- FAILURE ANALYSIS

FIGURE 3. LIM

KOH Concentration Effects on Initial Capacity of Ni/H2 Cells.

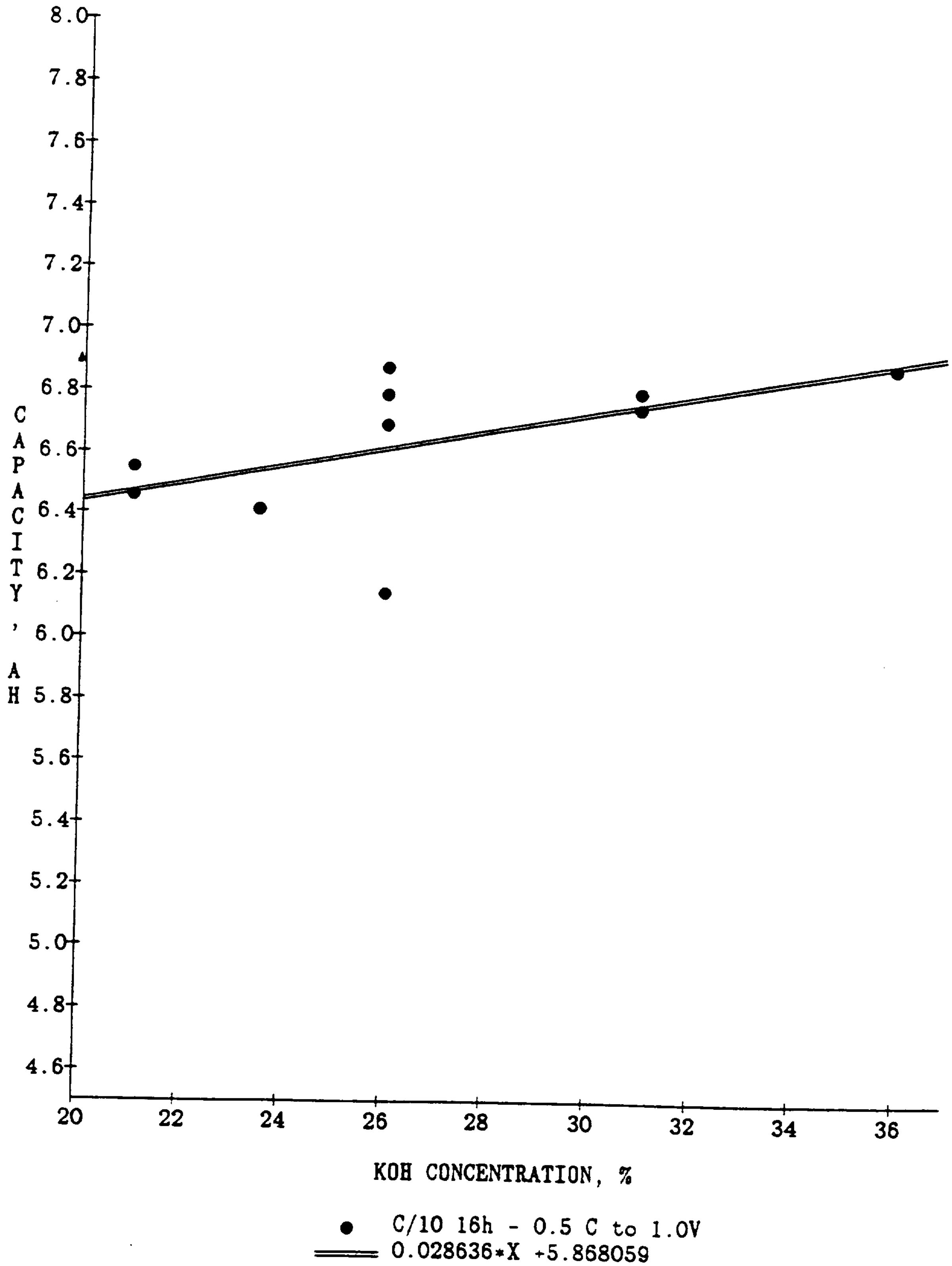


FIGURE 4. LIM

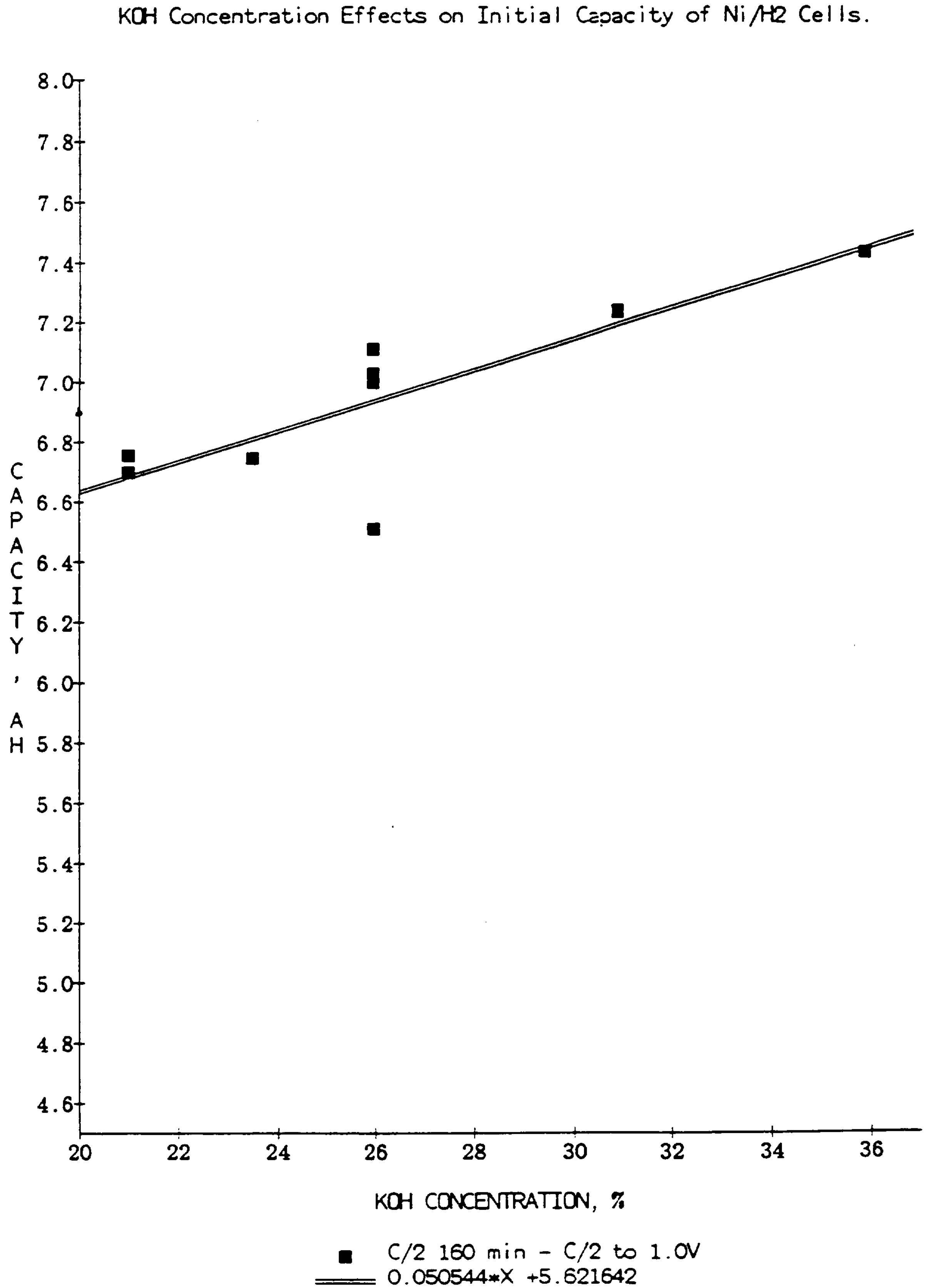

KOH Concentration Effects on Initial Capacity of Ni/H2 Cells.
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
CAPACITY, AH
20
22
24
26
28
30
32
34
36
KOH CONCENTRATION, %
C/2 160 min - C/2 to 1.0V
0.050544*X +5.621642

FIGURE 5. LIM

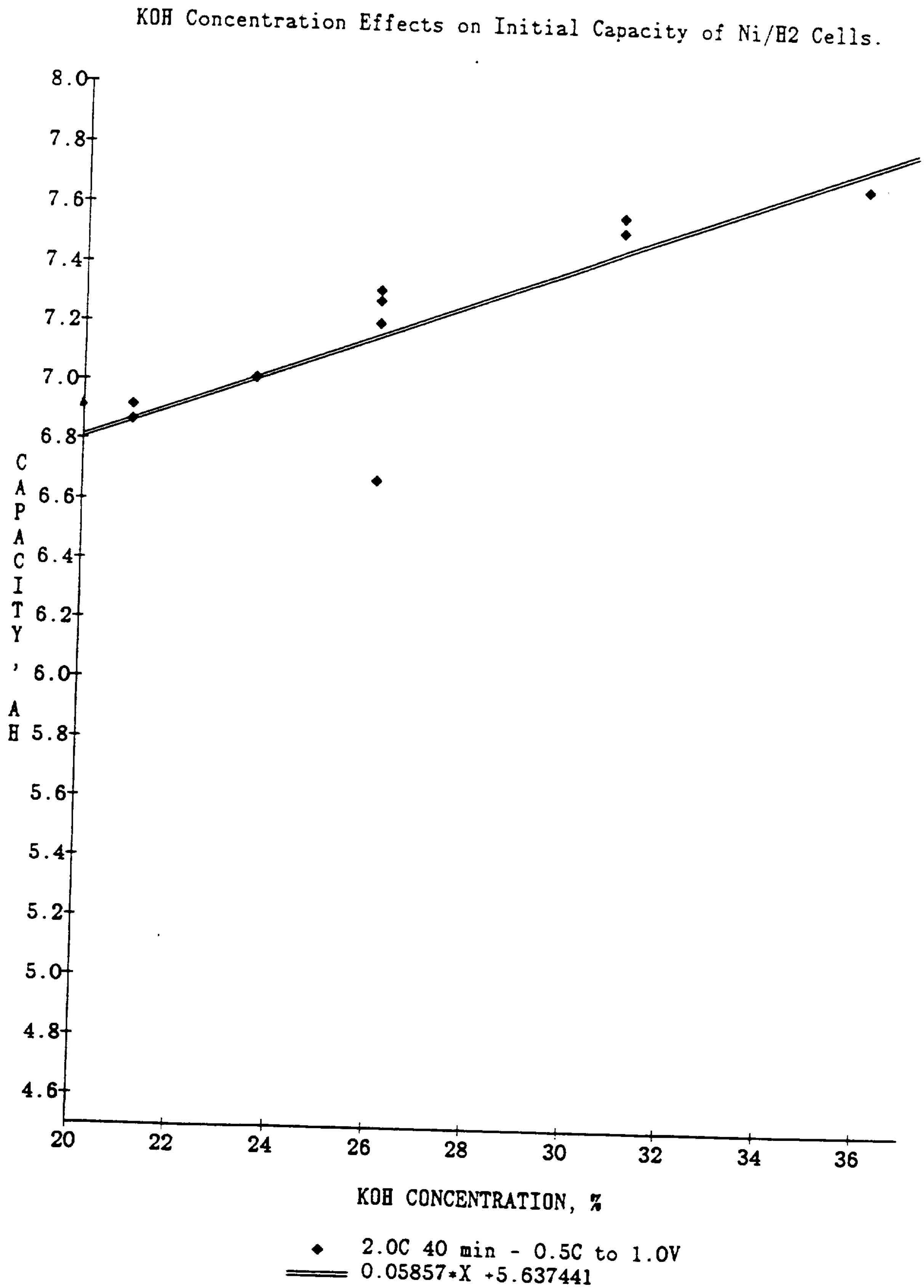
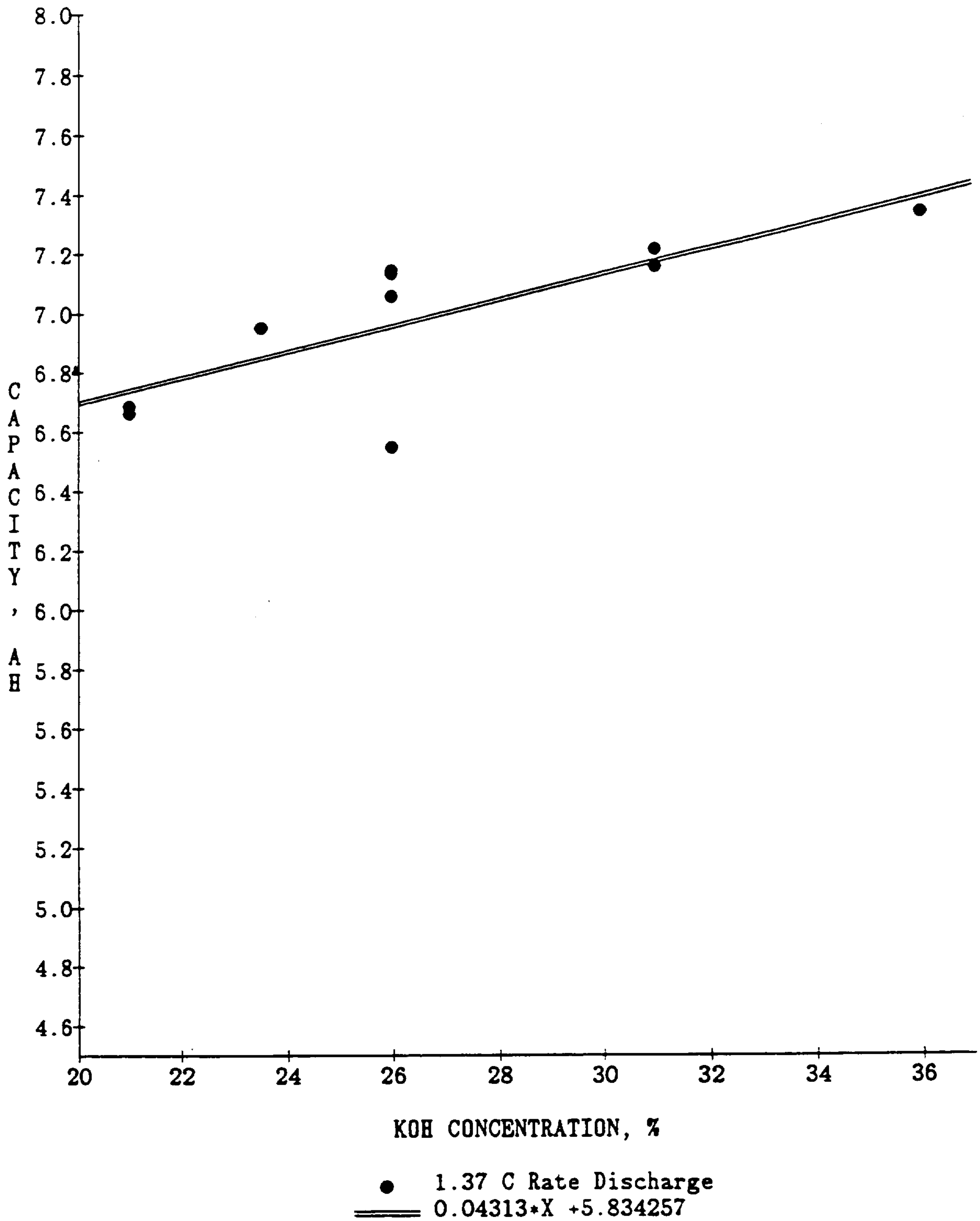

KOH Concentration Effects on Initial Capacity of Ni/H2 Cells.
CAPACITY, AH
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
20
22
24
26
28
30
32
34
36
KOH CONCENTRATION, %
2.0C 40 min - 0.5C to 1.0V
0.05857*X +5.637441

FIGURE 6. LIM

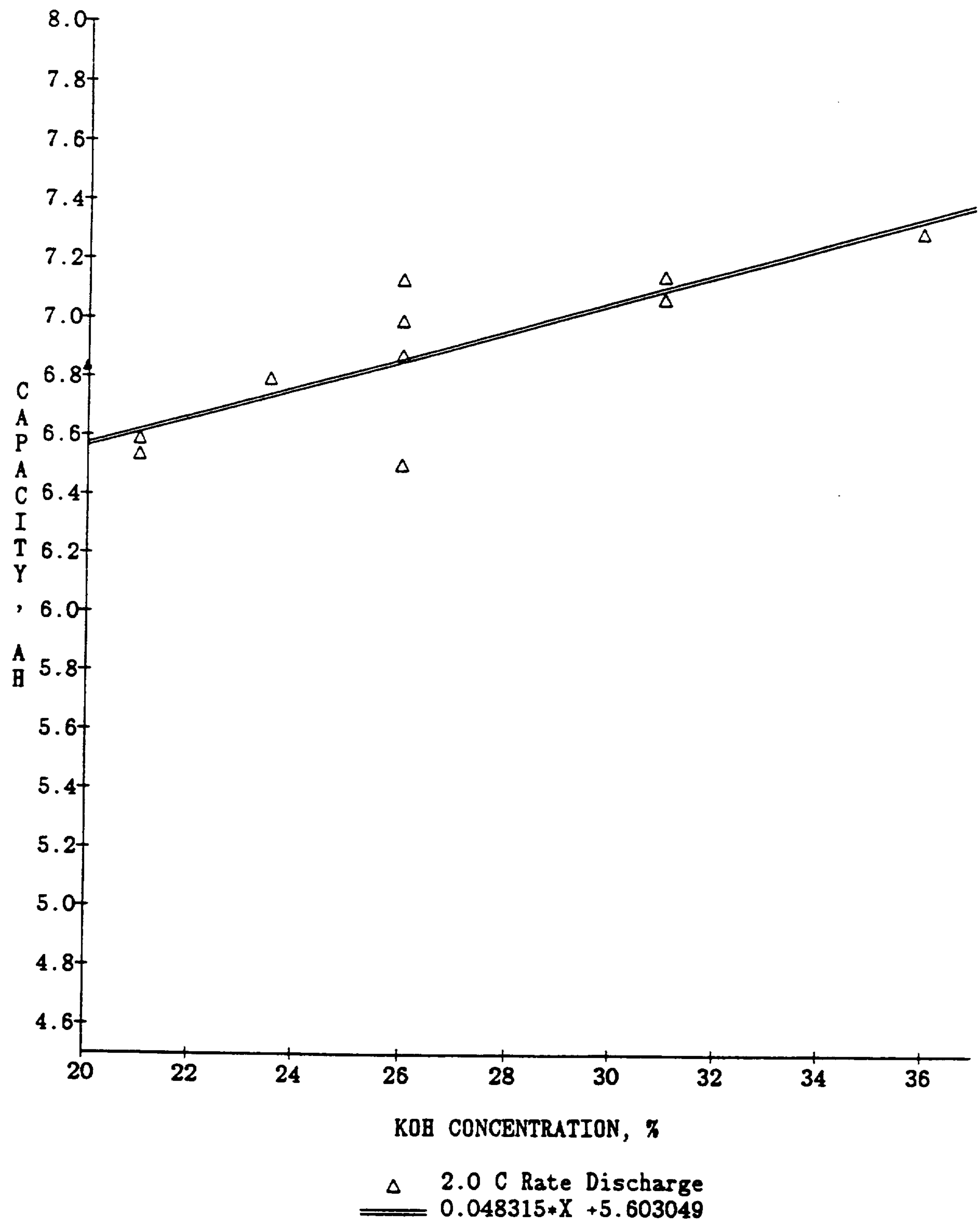
KOH Concentration Effects on Initial Capacity of Ni/H2 Cells.



Measured by charging cells for 80 min at 1.0 C rate and then discharging to 1.0 V.

FIGURE 7. LIM

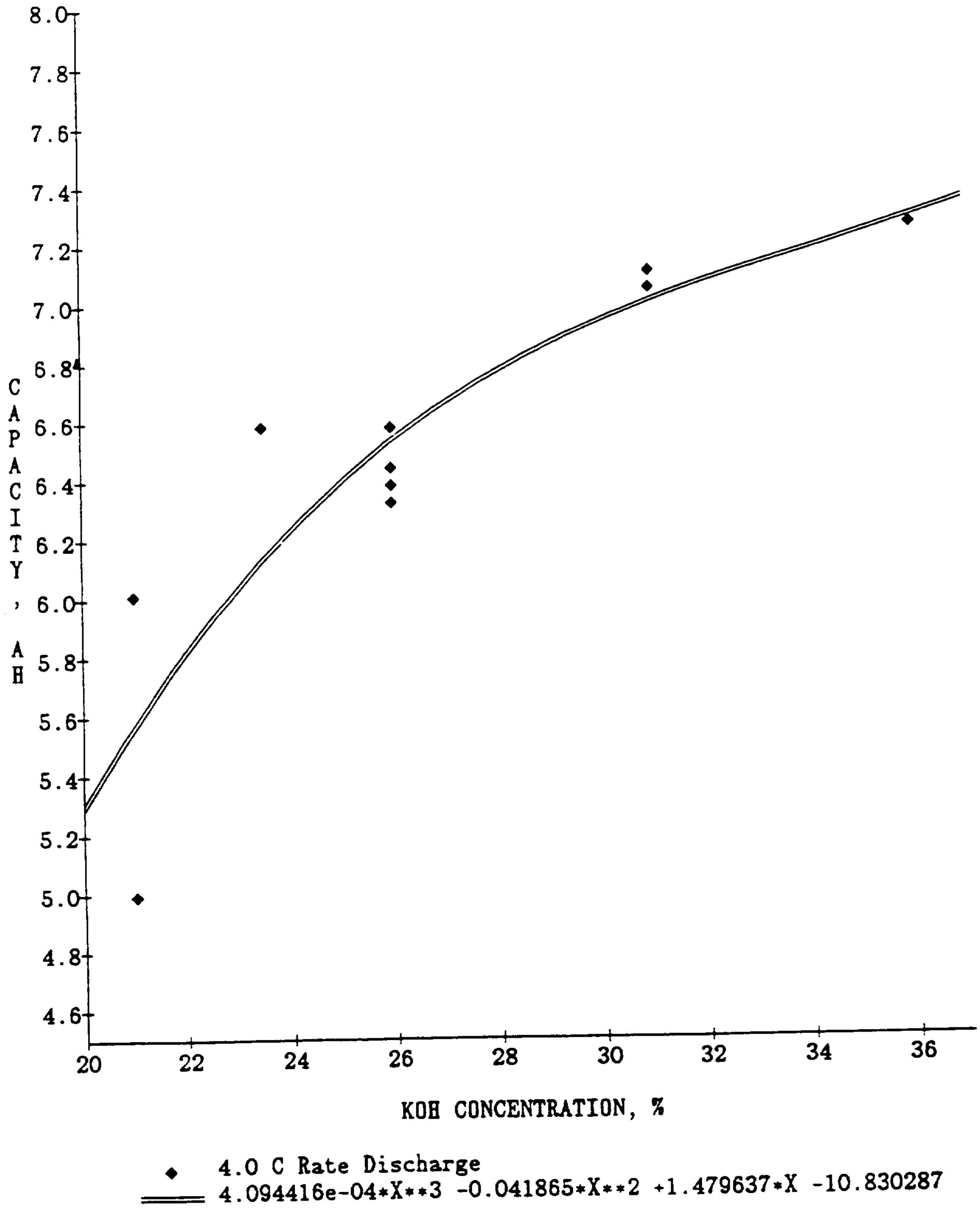
KOH Concentration Effects on Initial Capacity of Ni/H2 Cells.



Measured by charging cells for 80 min at 1.0 C rate and then discharging to 1.0 V.

FIGURE 8. LIM

KOH Concentration Effects on Initial Capacity of Ni/H2 Cells.



Measured by charging cells for 80 min at 1.0 C rate and then discharging to 1.0 V.

FIGURE 9. LIM

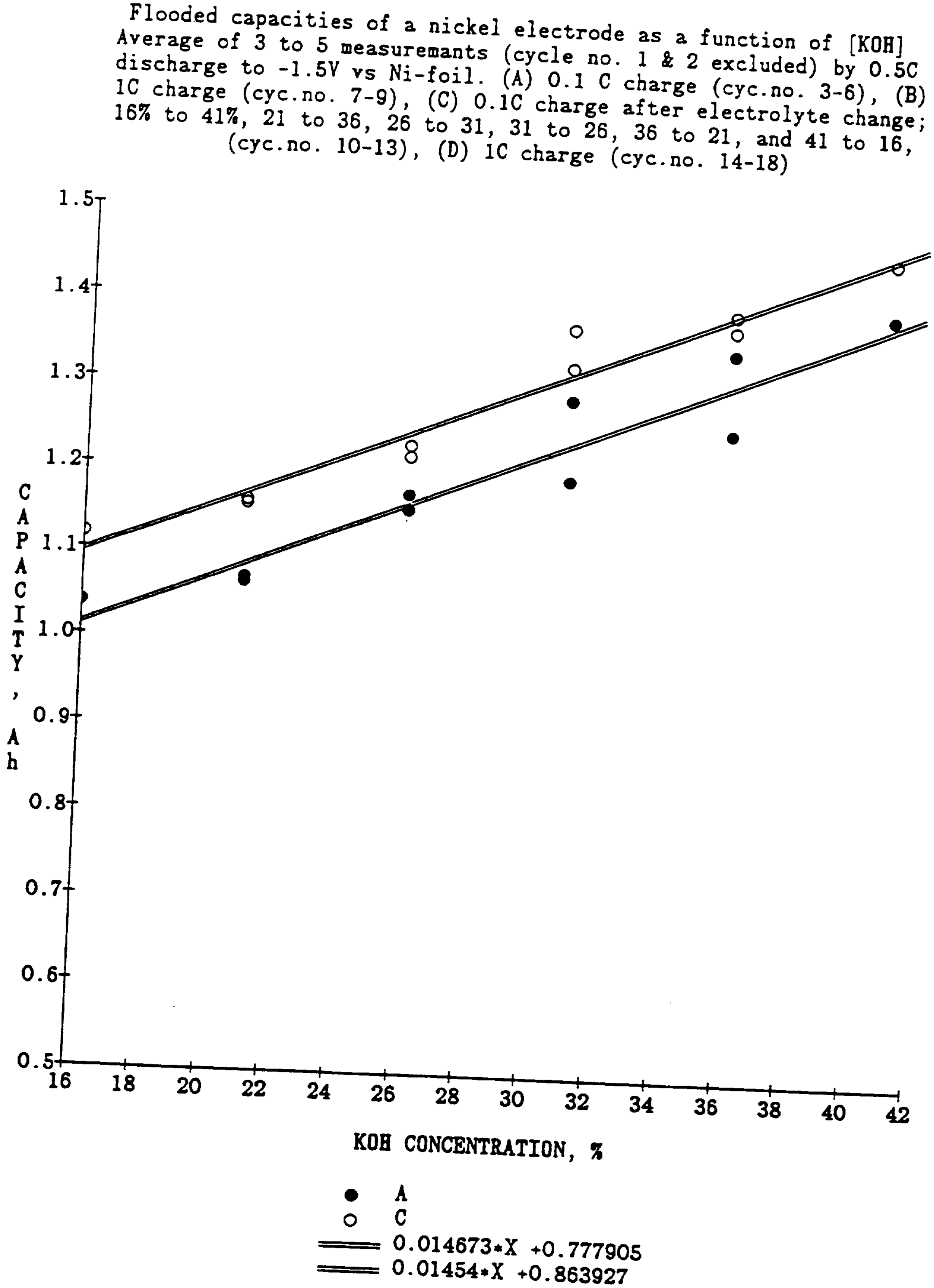


FIGURE 10. LIM

HUGHES

DISCHARGE CURVES AT 1.37C RATE 36% KOH (BP6)

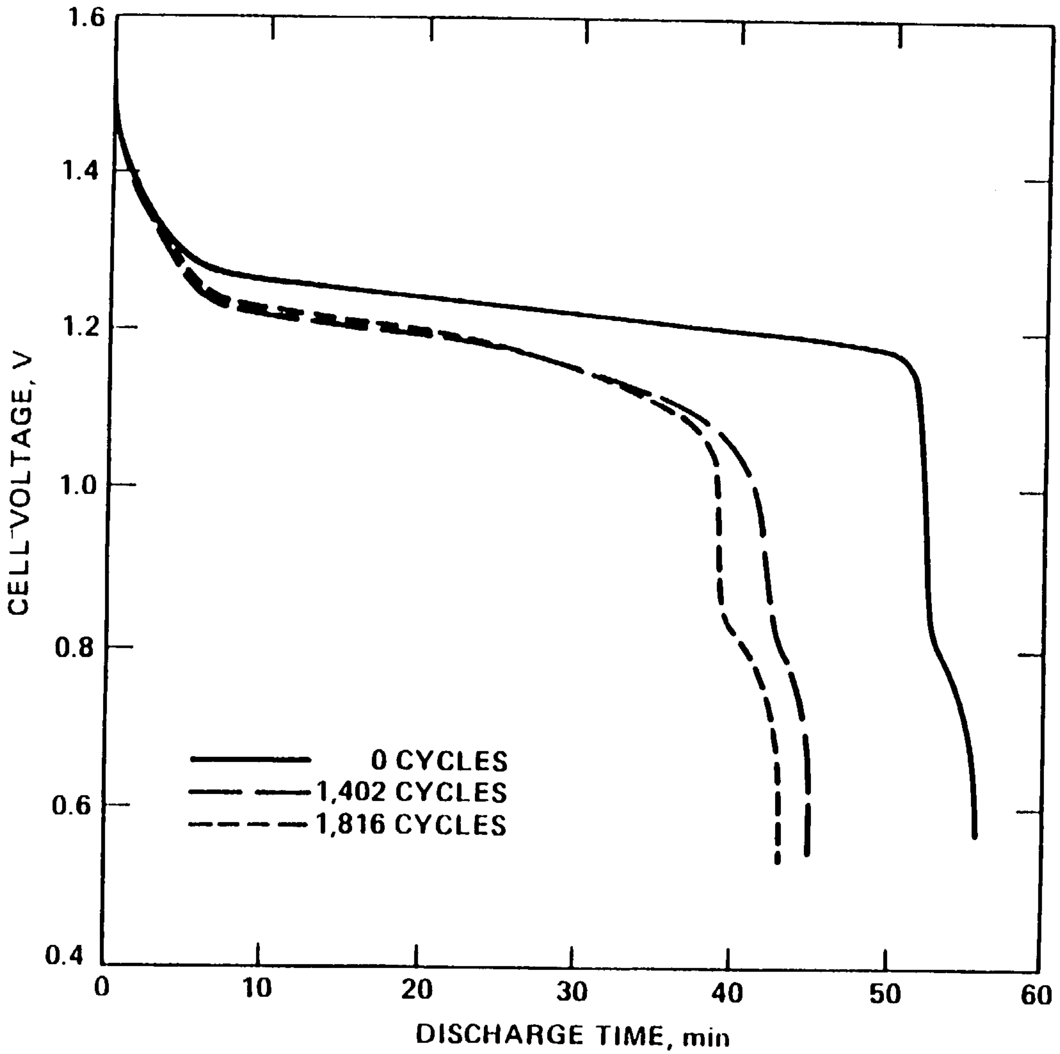
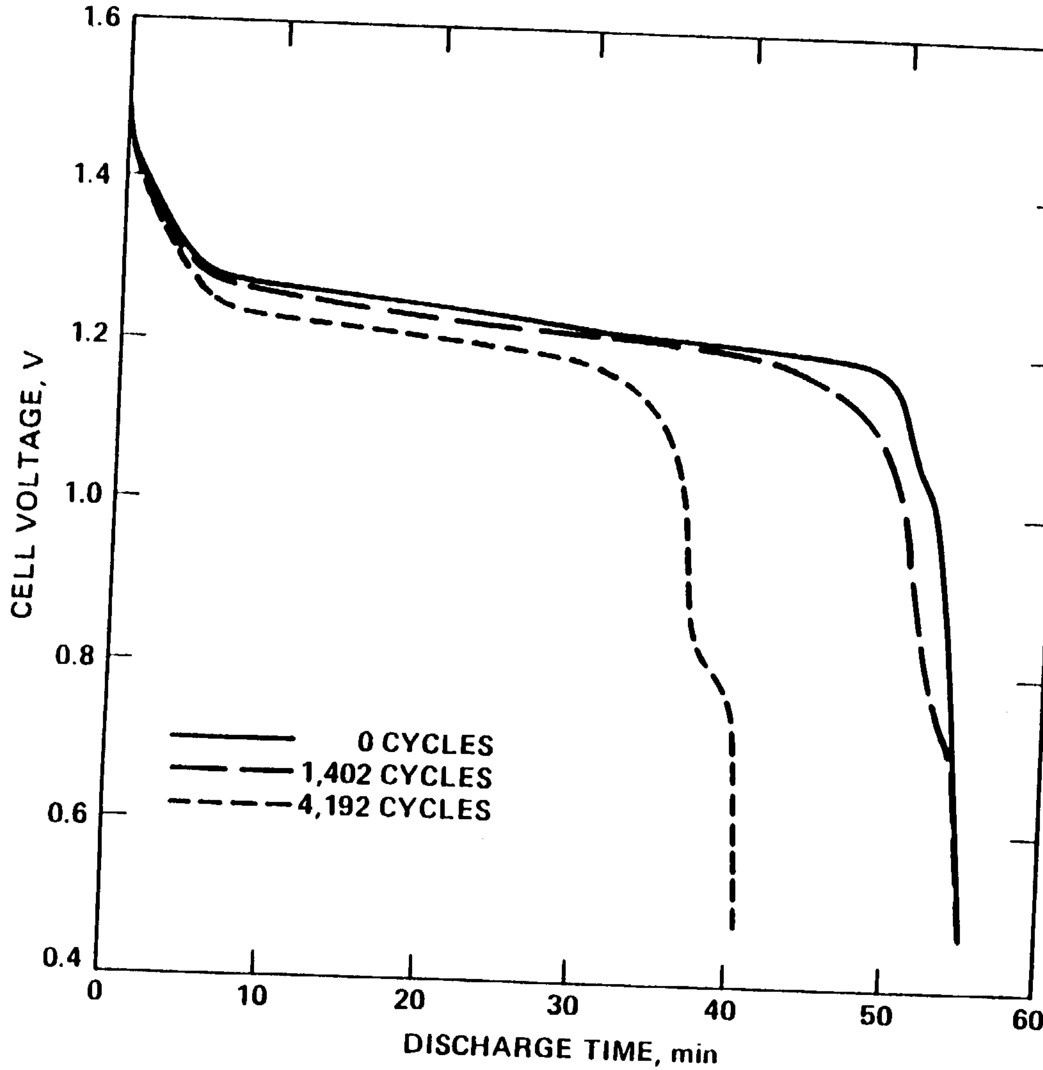


FIGURE 11 LIM

HUGHES

DISCHARGE CURVES AT 1.37C RATE 31% KOH (BP5)



DISCHARGE VOLTAGE TRACES OF INTERIM CAPACITY MEASUREMENTS OF BP2 CELL

HUGHES

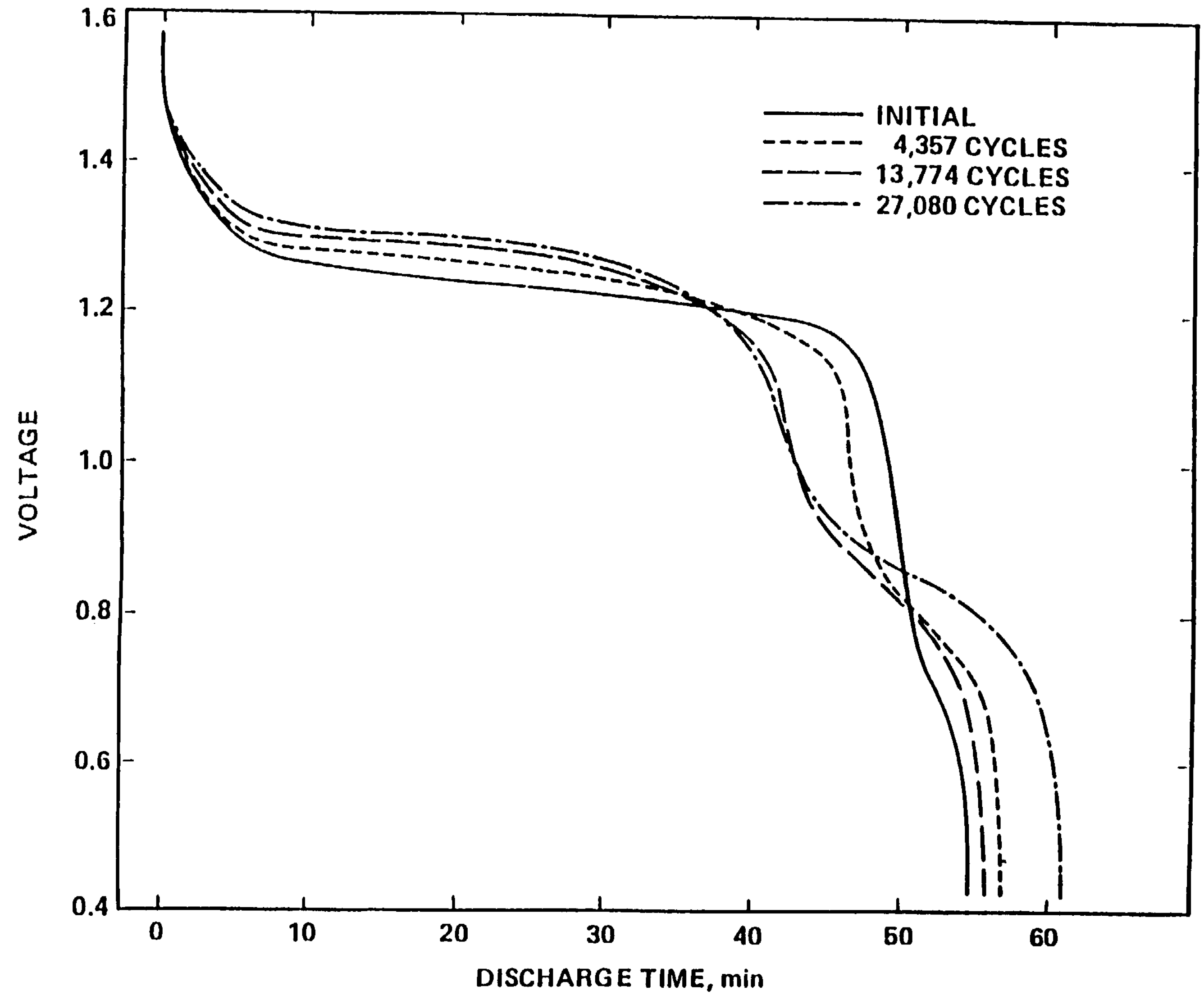


FIGURE 13. LIM

DISCHARGE VOLTAGE TRACES OF INTERIM CAPACITY MEASUREMENTS OF BP1 CELL

HUGHES

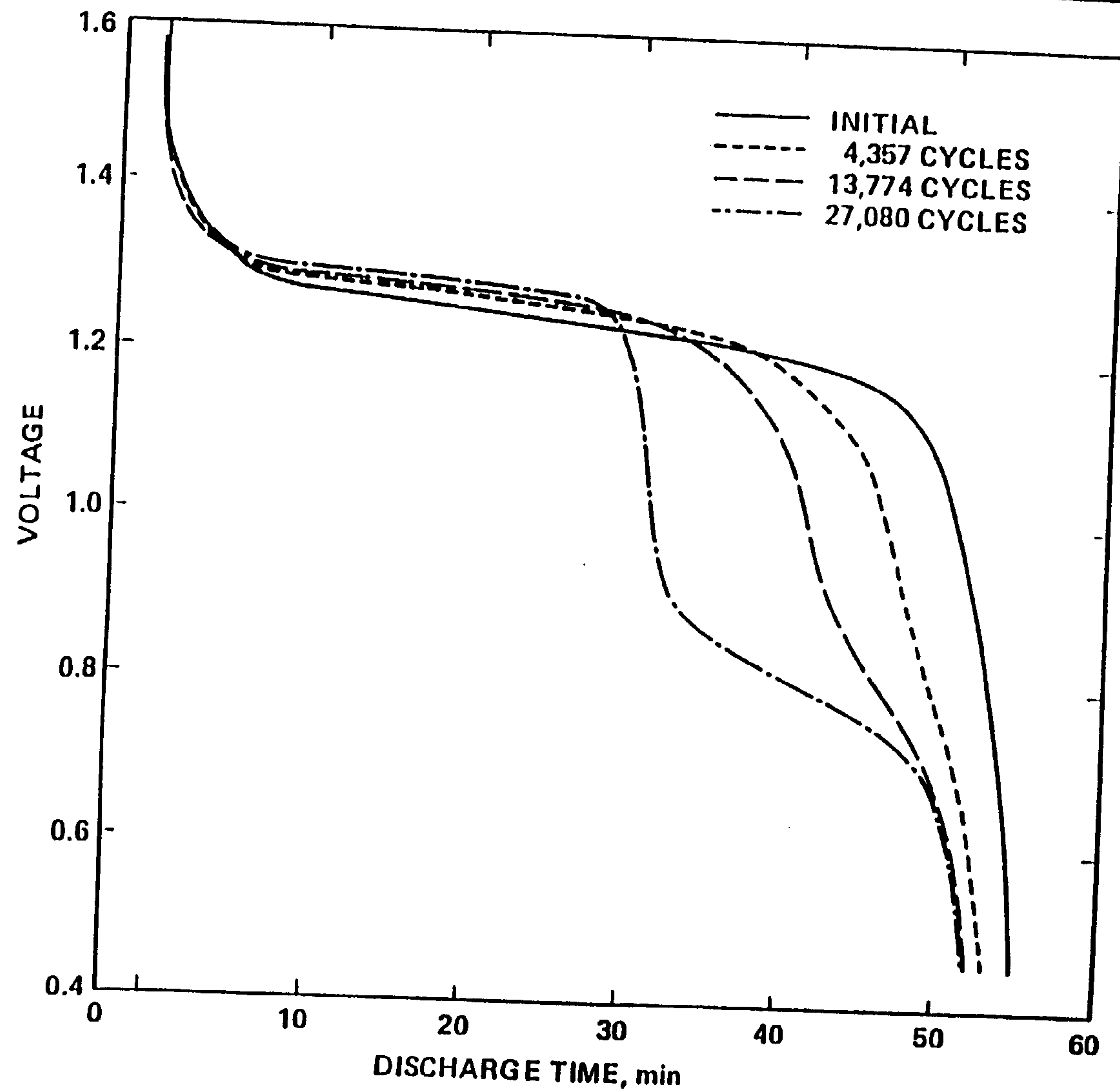


FIGURE 14. LIM

PLOTS OF EODV vs CYCLE NUMBER

VARIOUS KOH CONCENTRATIONS

HUGHES

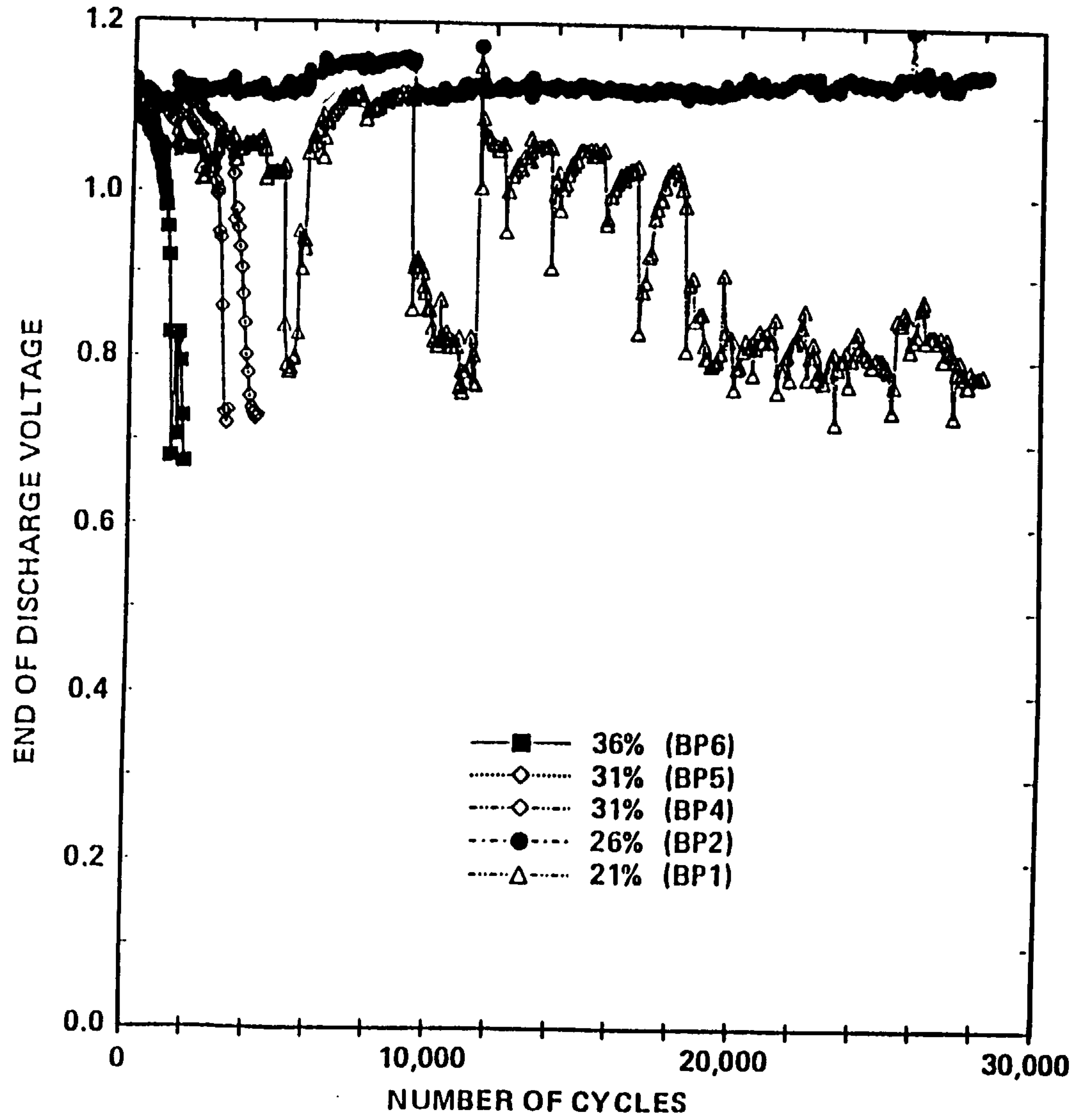


FIGURE 15. LIM

PLOTS OF EODV vs CYCLE NUMBER

VARIOUS KOH CONCENTRATIONS

HUGHES

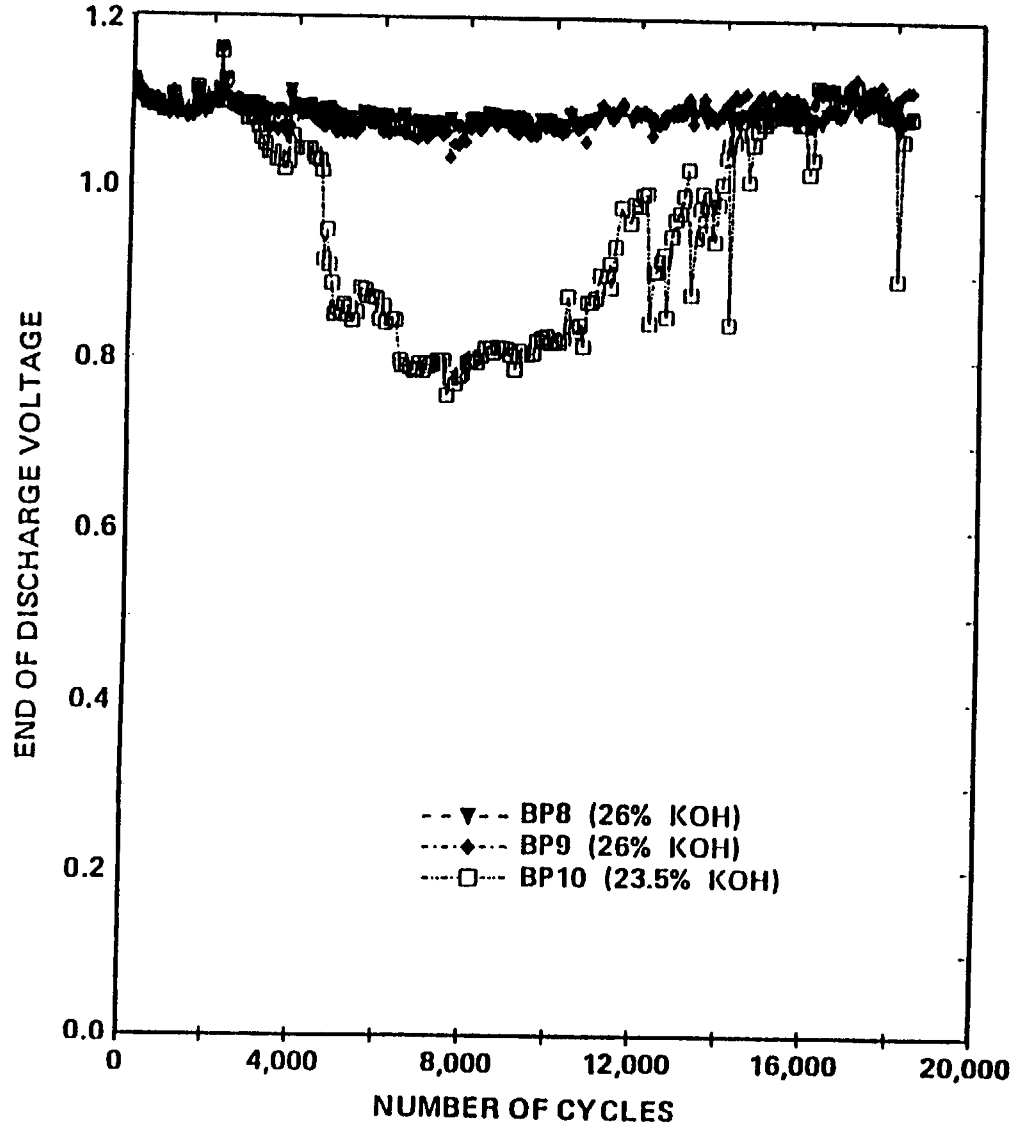


FIGURE 16. LIM

INTERIM CAPACITY OF TEST CELLS

80 MIN C RATE CHARGE–1.37 C RATE DISCHARGE TO 1.0V

HUGHES

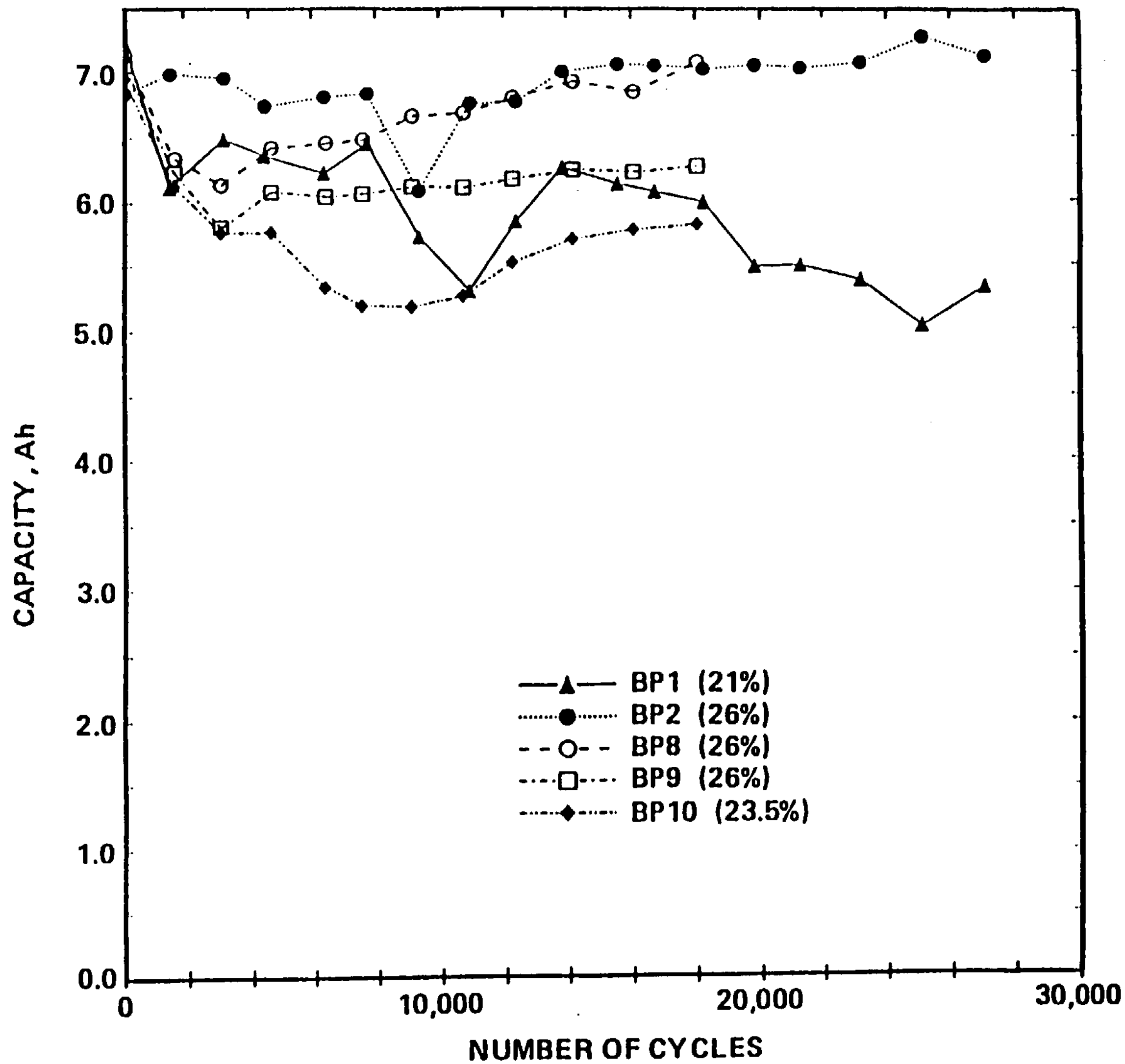


FIGURE 17. LIM

LIFE TEST RESULTS OF Ni/H_2 CELLS

— VARIOUS KOH CONCENTRATIONS —

HUGHES

CELL NO.	[KOH] %	NO. OF CYCLES TO 0.9 V	NO. OF CYCLES TO 0.5 V	CYCLING STATUS
BP1	21	5,047	>34,000	IN PROGRESS
BP7	21	1,037	6,508	REMOVED
BP10	23.5	4,803	>26,000	IN PROGRESS
BP2	26	>36,000	>36,000	IN PROGRESS
BP8	26	>26,000	>26,000	IN PROGRESS
BP9	26	>23,598	>24,600	REMOVED
BP3*	26	4,329	9,241	REMOVED
BP4	31	2,979	3,275	REMOVED
BP5	31	3,620	4,230	REMOVED
BP6	36	1,268	1,845	REMOVED

*TEARDOWN ANALYSIS OF THIS CELL SHOWED THAT THERE WAS A MECHANICAL DEFECT IN TAB-WELDING ON ONE OF THE HYDROGEN ELECTRODES.

FIGURE 18. LIM

SESSION V

PANEL DISCUSSION

THE MERITS OF CURRENT KOH CONCENTRATION IN USE FOR NiH_2 AND NiCd CELLS

Chairman: Dr. Lawrence Thaller, NASA/LeRC

PANEL SESSION

The last scheduled event of the Battery Conference was a Panel Discussion of the Merits of Current KOH Concentration in Use for NiH_2 and NiCd Cells. The panelists were Hong Lim (Hughes Aircraft) and Jim Dunlop (Comsat). Chairman Lawrence Thaller had posed general questions for the panel and these were presented by Dunlop, and then he gave his responses to them:

1. Concentration Effect

   A. Swelling characteristics--is it better to reduce the KOH concentration to avoid swelling?
   B. Oxygen evolution
   C. Hydrogen recombination
   D. Morphological
   E. Equilibrium crystalline

2. Which kind of nickel electrode?

   A. Chemically
   B. Aqueous
   C. Alcoholic

Dunlop said that everyone would agree that it is probably better to reduce the KOH concentrations. He commented that electrodes swell more with time than with the number of cycles. COMSAT research has shown that there has been migration of active material toward the surface.

Dunlop pointed out that the measured electrolyte concentration differs whether the cell is fully charged or fully discharged. This should be kept in mind when looking at Lim's data. The change was slightly masked in Lim's procedure.

Intelsat V and VI cells give better utilization than Lim's cells. Dunlop would go to 31 percent or lower in discharge for LEO applications.

Lim made the following remarks: The concentration of KOH does change with charge/discharge. He used a boiler plate cell and laid it on its side to equilibrate. He then righted it and charged it. Then he measured the KOH and the amp-hours. He couldn't find the change in KOH described by Dunlop.

Lim has three kinds of data on swelling. With lower KOH concentration there was lower expansion. Lim's work is confirmed by McDermott and also by Bell Labs work. With the boiler plate cells there was little difference in capacity between 26 percent and 31 percent KOH and some voltage advantage. The advantage comes out clearly with respect to longer life. Lim agreed that we need to confirm the change in KOH at charge vs discharge.

Dunlop said that when the cells are activated the KOH concentration is what we put in. He has no conflicting data in his data base. Lim said that his techniques are different from Dunlop's. Dunlop said that Lim's boiler plate has a greater amount of KOH and therefore a lesser change in KOH concentration.

Q. ________ : What was the method of impregnation used for the plates in the BP cell?

A. It was the same as used for the flight version.

Q. Thierfelder (GE Astro): Were all of Lim's tests done with boiler plate cells and all of Dunlop's with flight-type cells?

A. Dunlop (COMSAT): All but one were flight type and the one was boiler plate.

Q. Thierfelder (GE Astro): Was the difference in charge/discharge found in the boiler plate cells?

A. Dunlop (COMSAT): Yes

Dunlop said that it is important to specify which KOH concentration you are discussing. When you do an activation process you set the KOH at 31 percent. After you do a drain discharge you can set the KOH at 31 percent but you will get from 38 to 31 percent either way.

Q. ________ : Why does cycle life increase with reduced KOH?

A. Lim (Hughes Aircraft): There is some indication that the voltage increases with less "black powdering." This is consistent with crystallographic studies.

Q. Thierfelder (GE Astro): How about studying 28.5 percent KOH to see if there is a continuous change from 26 to 31 percent.

A. Lim (Hughes Aircraft): I haven't done it. Electrode changes are observed to be less at lower KOH.

Q. _______ : In an earlier paper I reported on studying flooding capacities with changes in KOH. I got an S-shaped curve. Near mid 20s (percent KOH) there were big changes and then they levelled off near 35 percent. The electrodes were aqueous electrochemically impregnated.

Dunlop stated that for all of the Intelsat V and VI studies he got the same utilization for aqueous and alcohol impregnation with flooded electrolytes.

Lim said Joe and he got different results for 31 to 26 percent. There may have been a difference in the electrodes. Lim had ten cells with duplicate measurements--he was reporting the average of 3 to 5 measurements. Dunlop asked whether any cells with different concentrations were to be included in Thaller's studies. Thaller said he'd be doing 26 and 31 percent KOH

Q. Hall (Whittaker-Yardney): What was the change in capacity in going from 26 to 31 percent in the early cycles?

A.

Q. Sindorf (NASA LeRC): When you charged the boiler plate cells was there any discharge state?

A. Lim: Yes

Q. Sindorf (NASA LeRC): We put in electrolyte when the electrodes are fully dry.

A. Lim: The electrolyte was filled under vacuum and drained after an overnight short.

Q. Sindorf (NASA LeRC): We had the 26 percent KOH freeze at -20 degrees C.

Dunlop said that the -20 degrees C freezing suggested a lower concentration of KOH.

Q. ______ : What were the types of electrodes?

A. Lim (Hughes Aircraft): We had alcohol electrochemically impregnated.

The Battery Conference adjourned at 4 p.m. on Thursday November 5, 1987.

POWER TECHNOLOGY DIVISION

Lewis Research Center

GENERAL QUESTIONS FOR THE PANEL

1. DOES, WOULD, OR DO YOU EXPECT THAT THE ELECTROLYTE CONCENTRATION EFFECT:

   a. THE SWELLING CHARACTERISTICS

   b. THE OXYGEN EVOLUTION CHARACTERISTICS

   c. THE HYDROGEN RECOMBINATION CHARACTERISTICS

   d. THE MORPHOLOGICAL ASPECTS

   e. THE EQUILIBRIUM CRYSTALLINE PHASE/PHASES PRESENT OF A NICKEL ELECTRODE?

2. WHICH KIND OF NICKEL ELECTRODE:

   a. CHEMICALLY IMPREGNATED, b. AQUEOUS OR c. ALCOHOLIC PROCESS?

FIGURE 1. PANEL SESSION

Dear Jim and Hong,

I plan to make this sheet up into a slide to put up following your introductory remarks of about 10 minutes each. It may get the discussion going. You fellows can bring up your own pet opinions or biasses in the introduction portion. Thanks a lot for being willing to participate in this.

Larry

GENERAL QUESTIONS FOR THE PANEL

1. DOES, WOULD, OR DO YOU EXPECT THAT THE ELECTROLYTE CONCENTRATION EFFECT:

   a. THE SWELLING CHARACTERISTICS

   b. THE OXYGEN EVOLUTION CHARACTERISTICS

   c. THE HYDROGEN RECOMBINATION CHARACTERISTICS

   d. THE MORPHOLOGICAL ASPECTS

   e. THE EQUILIBRIUM CRYSTALLINE PHASE/PHASES PRESENT

   -OF A NICKEL ELECTRODE?

2. WHICH KIND OF NICKEL ELECTRODE:

   a. CHEMICALLY IMPREGNATED, b. AQUEOUS OR c. ALCOHOLIC PROCESS?

FIGURE 2. PANEL SESSION

COMPARISON OF 26% KOH VS 31% KOH FOR A Ni/H_2 CELL

ADVANTAGES OF 26% KOH

- LONGER CYCLE LIFE AT THE SAME **ABSOLUTE** DOD OPERATION
- VOLTAGE INCREASE (VS DECREASE WITH 31%) WITH CYCLING
  31%; 20~30 mV DECREASE AFTER 3,000 CYCLES
  26%; 10~20 mV INCREASE AFTER 3,000 CYCLES
  20~25 mV INCREASE AFTER 20,000 CYCLES

Stockel 85, IECEC.
25% Av. Disch. V = 1.290
31% " = 1.268
ΔV 22 mV

- SLOWER RATE OF NICKEL ELECTRODE EXPANSION
- LESS "BLACK POWDER" FORMATION ON NICKEL ELECTRODE
- LOWER DENSITY: 4% @ 25°C
- HIGHER O_2 SOLUBILITY: 1.77 TIMES
  AT 25°C; 1.1×10^{-4} M (26%) vs 6.2×10^{-5} M (31%)
- SLIGHTLY HIGHER CONDUCTIVITY

DISADVANTAGES

- SMALLER INITIAL CAPACITY BY 3~5%
- HIGHER FREEZING POINT:
  31%; ~-65°C
  26%; ~-40°C

Expansion

- Bernhart + Mauer, 1980
  $\frac{\text{Rate in 20\% KOH}}{\text{Rate in 30\% KOH}} = \frac{1}{3}$
- McDermott, 1982

FIGURE 3. PANEL SESSION

P. MacDermott, 1981

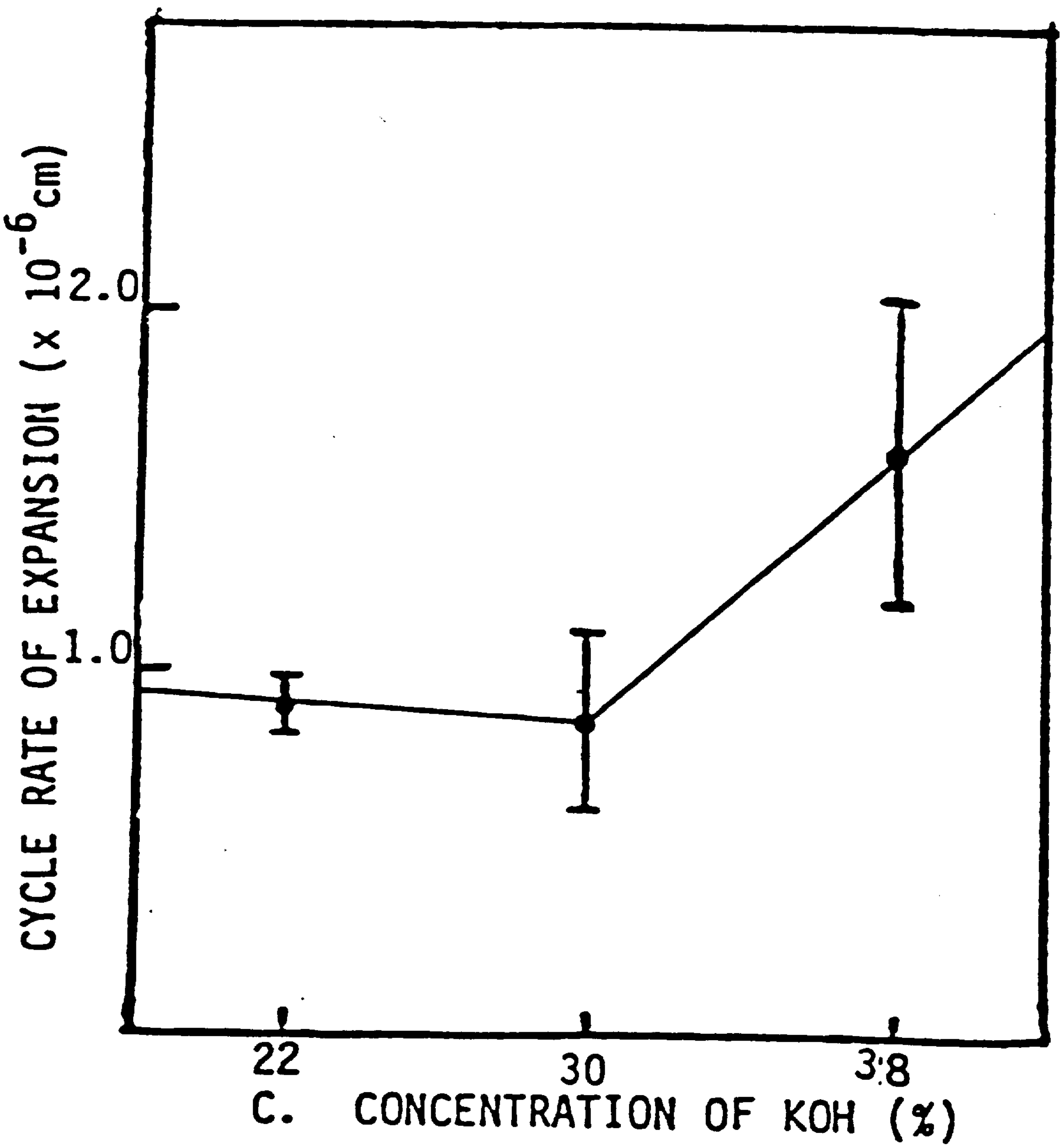


FIGURE 4. PANEL SESSION

End of discharge voltages vs cycle number of nickel-hydrogen boiler plate cells having electrolytes of various KOH concen.

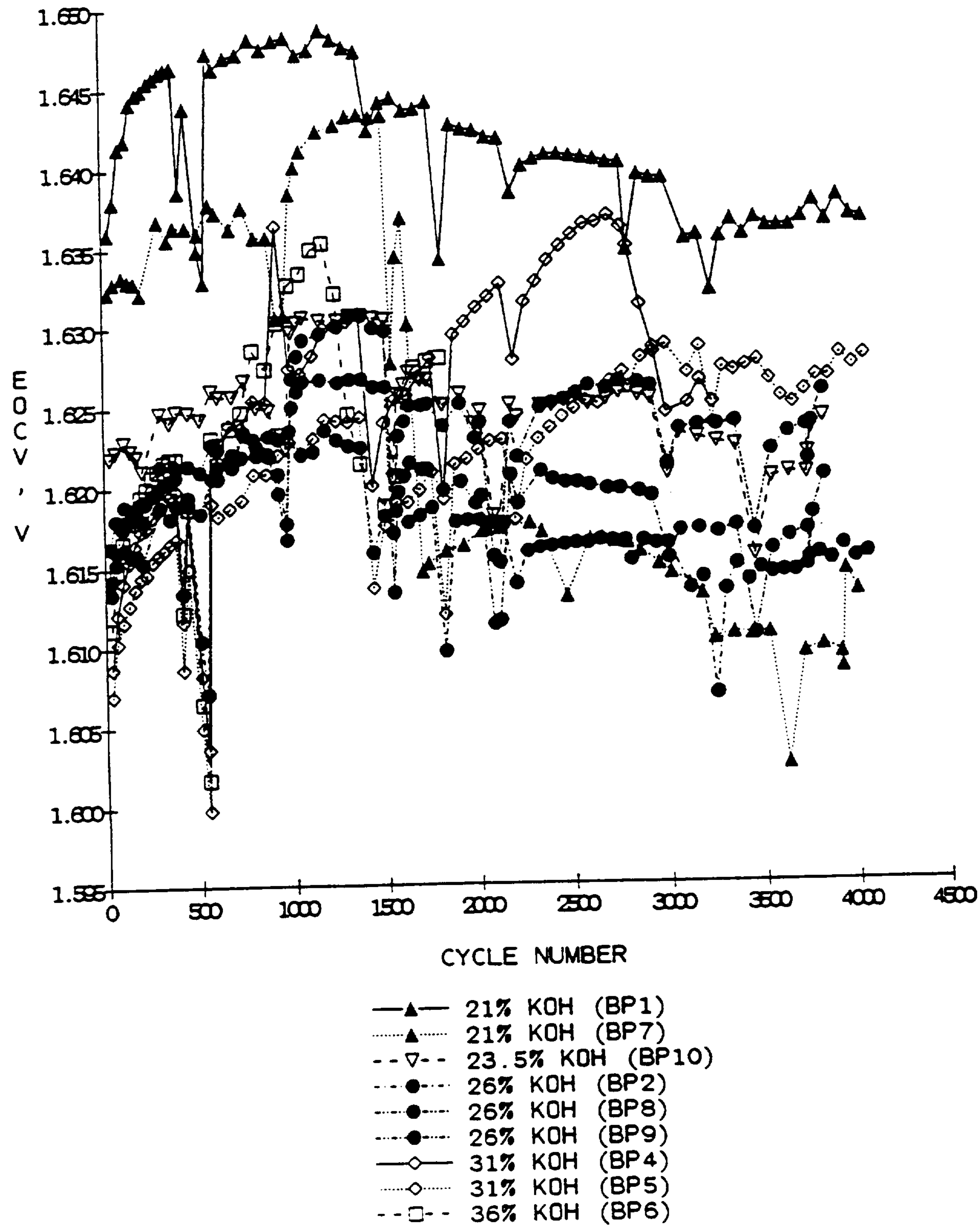


FIGURE 5. PANEL SESSION

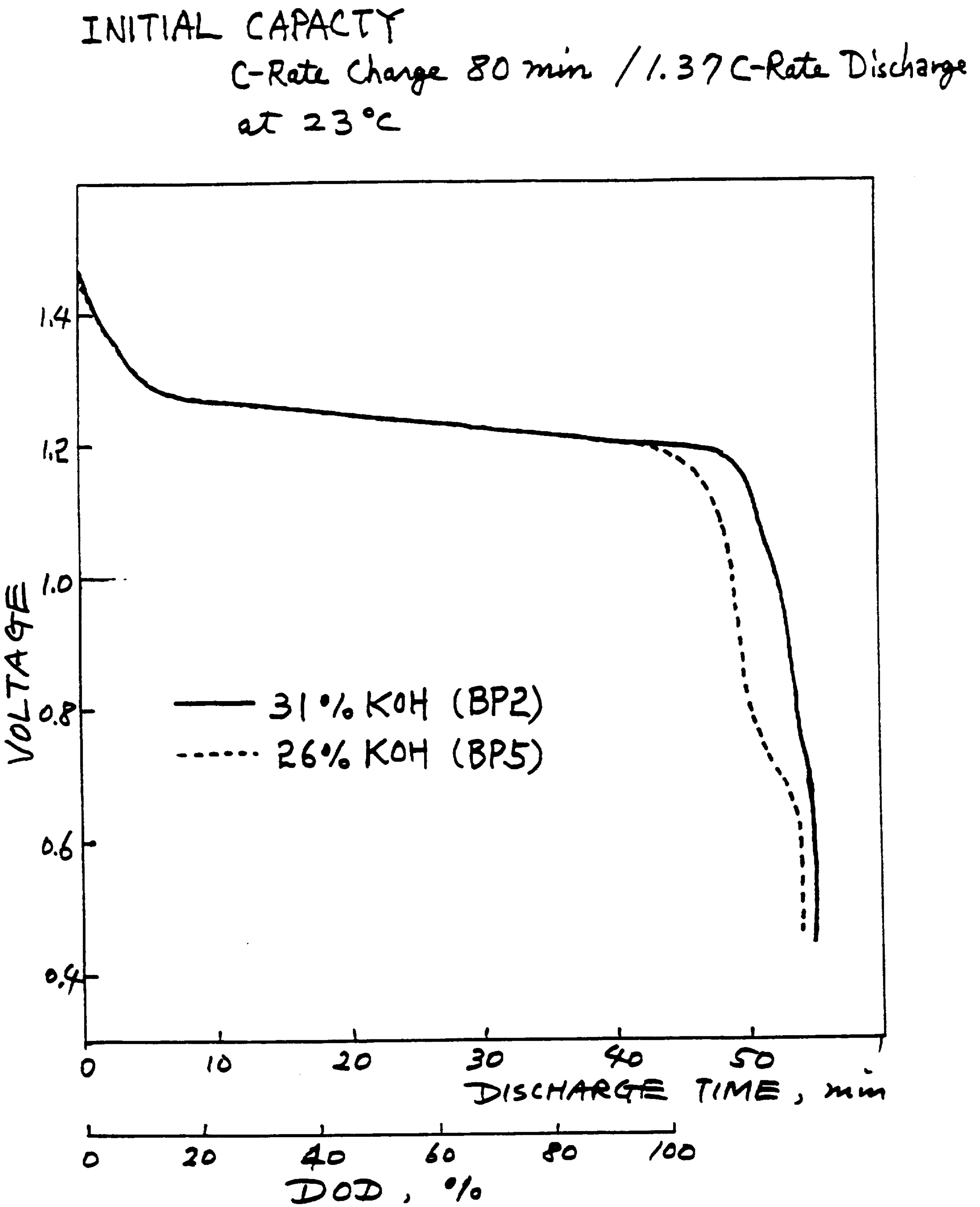


FIGURE 6. PANEL SESSION

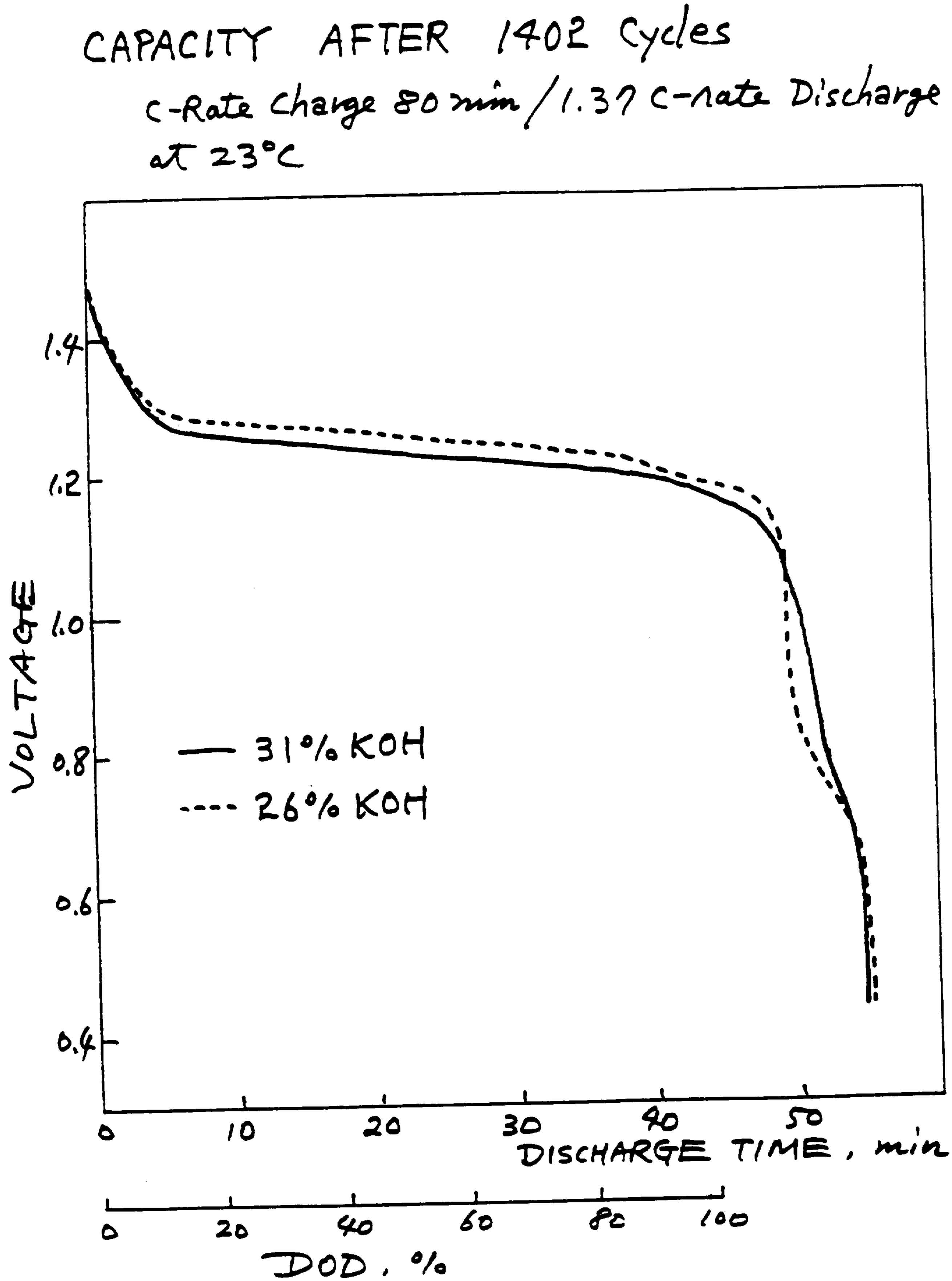


FIGURE 7. PANEL SESSION

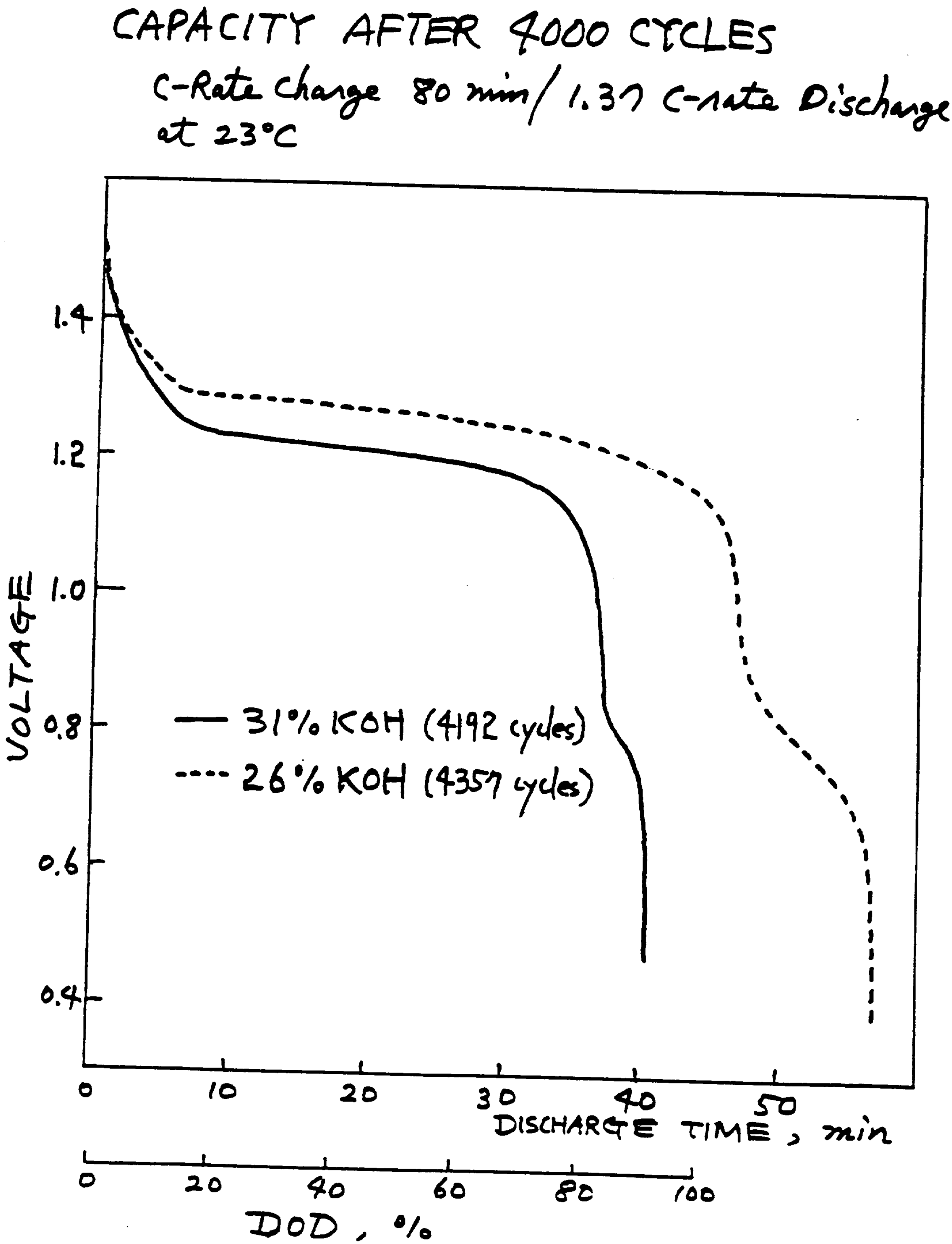


FIGURE 8. PANEL SESSION

COMPARISON OF 26% KOH VS 31% KOH FOR A Ni/H_2 CELL

ADVANTAGES OF 26% KOH

- LONGER CYCLE LIFE AT THE SAME **ABSOLUTE** DOD OPERATION
- VOLTAGE INCREASE (VS DECREASE WITH 31%) WITH CYCLING
  31%; 20~30 mV DECREASE AFTER 3,000 CYCLES
  26%; 10~20 mV INCREASE AFTER 3,000 CYCLES
  20~25 mV INCREASE AFTER 20,000 CYCLES
- SLOWER RATE OF NICKEL ELECTRODE EXPANSION
- LESS "BLACK POWDER" FORMATION ON NICKEL ELECTRODE
- LOWER DENSITY: 4% @ 25°C
- HIGHER O_2 SOLUBILITY: 1.77 TIMES
  AT 25°C; 1.1×10^{-4} M (26%) vs 6.2×10^{-5} M (31%)
- SLIGHTLY HIGHER CONDUCTIVITY

DISADVANTAGES

- SMALLER INITIAL CAPACITY BY 3~5%
- HIGHER FREEZING POINT:
  31%; ~-65°C
  26%; ~-40°C

FIGURE 9. PANEL SESSION

CONCLUDING REMARKS

- BP CELLS / ACCELERATED TEST RESULTS SHOW CLEAR MERITS OF 26% KOH OVER 31% KOH FOR A Ni/H_2 CELL ESPECIALLY FOR LONG CYCLE LIFE APPLICATIONS.
- FULL EVALUATION OF 26% KOH ELECTROLYTE IN FLIGHT CELLS IS STRONGLY RECOMMENDED TO CONFIRM THIS MERITS.

FIGURE 10. PANEL SESSION

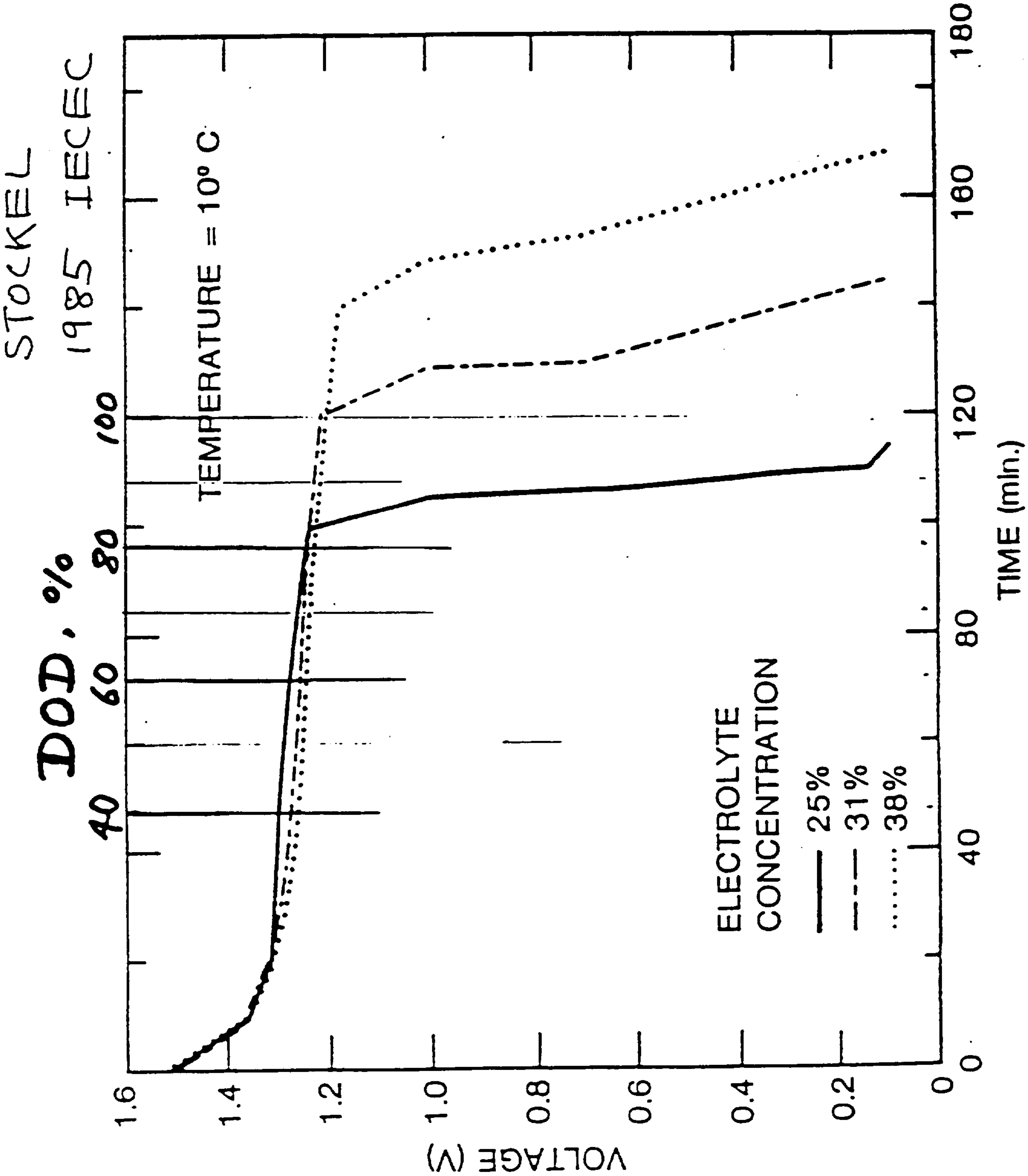
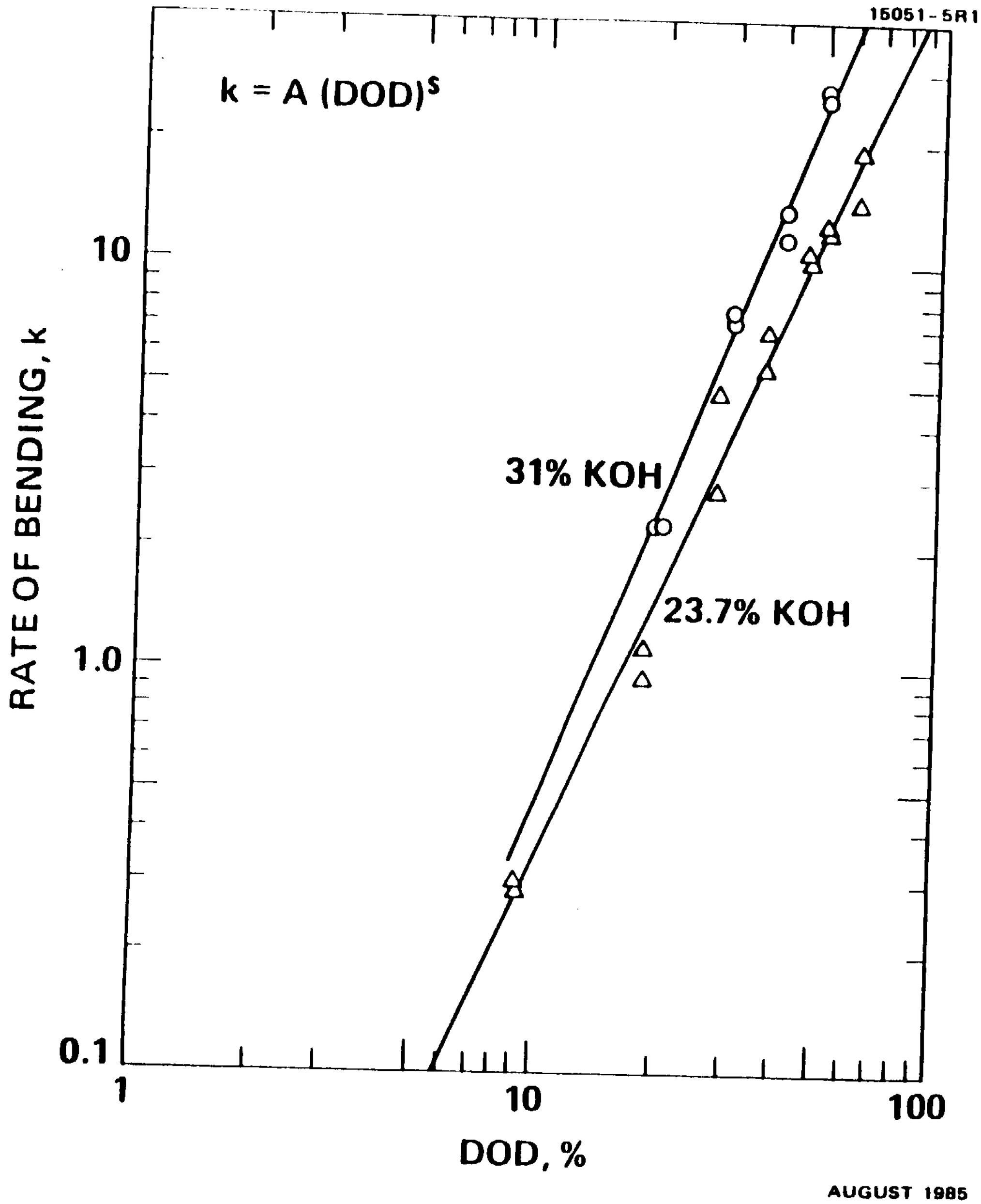


FIGURE 11. PANEL SESSION



HUGHES

EFFECT OF DEPTH-OF-DISCHARGE ON ELECTRODE EXPANSION RATE

FIGURE 12 PANEL SESSION

LIST OF ATTENDEES

1987 NASA/GSFC BATTERY WORKSHOP
LIST OF PARTICIPANTS

John Andrasik
NASA Lewis Research Center
MS 500-211
21000 Brockpark Road
Cleveland, OH 44135
(216)433-2350

Remi Asplanato
Aerospatiale
BP 99
100, Bd dn Thidi
06322 Cannes La Bocca
Cedea
92927000

Daniel Augenstene
DOJ
8199 Backlick Rd.
Lorton, VA 22079
(202) 324-2800

Charles Badcock
Aerospace Corporation
P.O. Box 92957
Mail Stop M2-275
Los Angeles, CA 90009
(213) 336-4103

James Barnes
NSWC
Code R33
Silver Spring, MD 20903-5000
(301) 394-1312

David Baer
Hughes Aircraft Co.
MS A315
P.O. Box 92919 Bldg. S41
LA Airport Sation
Los Angeles, CA 90009

Carl Baxam
TRACOR Battery
3805 Mt. Vernon Ave.
Alexandria, VA 222305
(703)769-6833

E.R. Berry
Aerospace Corp.
P.O. Box 92957
Mail Stop M4/988
Los Angeles, CA 90009-2957
(213) 336-6273

Samuel Birken
Aerospace Corp.
P.O. Box 92957
Mail Stop M4 986
Los Angeles, CA 90009
(213) 336-6080

Frank Bis
Advanced Power Sources Inc.
5513 Ridge Rd.
Mt. Airy, MD 21771
(301) 831-7469

Carole Bleser
Eagle-Picher
3820 S. Hancock Expressway
Colorado Springs, CO 80911
(303) 392-4266

Francis R. Boyce
RCA
13305 Finsbury Ct. #1
Laurel, MD 20708
(301) 763-7577

Robert Bragg
NASA/JSC
MS EP5
NASA Road 1
Houston, TX 77058
(713) 483-9060

Marc Brideau
Martin-Marietta
10111 City View Dr.
Morrison, CO 80465
(303) 971-8286

Jack Brill
Eagle-Picher Industries, Inc.
P.O. Box 47
Joplin, MO 64802
(417) 623-8000

Richard J. Broderick
GTE Spacenet
4398 Canterbury Lane
Gainesville, VA 22065
(703) 848-0421

Michael Brookman
DME Corp.
111 Southwest 33 St.
Ft. Lauderdale, FL 33315

Kathleen Burch
COMSAT
19725 Purple Martin Lane
Gaithersburg, Maryland 20879
(301) 428-4000 Ext. 225

Robert Byrnes
Dept. of Army
27 Kelvin Dr.
Stafford, VA 22554
(202) 695-3516

Peter J. Cannon
American Cyanamid Co.
P.O. Box 34
Edgewater, MD 21037
(202) 471-9933

Stan Canter
QUADRI Corporation
952 S. 52nd St.
Tempe, AZ 85281
(602) 921-9933

Uno Carlsson
Fairchild Space Co.
MS A-28
20301 Century Blvd.
Germantown, MD 20874-1181
(301) 428-6022

Howard E. Carpenter
Gould Inc.
35129 Curtis Blvd.
Eastlake, Ohio 44094
(216) 953-5065

Robert Cataldo
NASA/Lewis Research Center
21000 MS 501-1
Brookpark Rd.
Cleveland, OH 44135
(216) 433-5254

Leo Christensen
Freudenberg Nonwovens
20 Industrial Avenue
Chelmsford, MA 01824
(617) 256-6588

James Ciesla
DME Corp.
111 Southwest 33 St.
Ft. Lauderdale, Fl 2331
(305)463-5066

Karla Clark
JPL
MS 277-212
4800 Oak Grove Dr.
Pasadena, CA 91109
(818) 354-9033

William Clark
Wilson Greatbatch Ltd.
10,000 Wehrle Dr.
Clarence, NY 14031
(716) 759-6901

Robert Cool
COMSAT
22300 COMSAT Drive
Clarksburg, MD 20871
(301) 428-4275

Frank Cushing
3-E LABS
840 W. Main Street
Landsdale, PA 19446

Harry Culver
NASA/Goddard Space Flight Center
Code 711
Greenbelt, Maryland 20771
(301) 286-6841

George Dakermanji
Fairchild Space Co.
MS A-28
20301 Century Blvd.
Germantown, MD 20879
(301) 428-6394

Ivan F. Danzig
U.S. Army
Pentagon
Washington, DC
(202) 695-3516

Eric C. Darcy
NASA-JSC
Mail Code EP5
Houston, TX 77058
(713) 483-9055

Anne de Guibert
Laboratories de Marcoussis
Route de Nozay
91.460 Marcoussis France

Michael Donnelly
Ford Aerospace (LANDSAT)
c/o NASA/Goddard Space Flight Center
Code 050.0
Greenbelt, Maryland 20771
(301) 286-2147

Orville O. Dunham Jr.
National-Standard Company
Industrial Blvd.
P.O. Box 1620
Corbin, KY 40701
(606) 528-2141

James Dunlop
COMSAT
COMSAT Laboratories
Clarksburg, Maryland 20734
(301) 428-4545

Andrew Dunnet
INTELSAT
3400 International Dr., NW
Washington, DC 20008
(202) 944-7245

Martin Earl
COMSAT Labs
22300 Comsat Dr.
Clarksburg, MD 20871
(301) 428-4503

Tim Edgar
Eagle - Picher Industries, Inc.
3820 S. Hancock Expy.
Colorado Springs, CO 80911
(303) 392-4266

Larry Edsinger
NASA/ARC
MS 213-2
Moffet Field, CA 94035
(415) 694-4079

Vickie Edwards
AT&T Bell Labs
Rm 1E207
600 Mountain Ave.
Murray Hill, NJ 07974
(201) 582-3286

Michael Fabre
Aerospatiale
B.P. 99 100, Bd du Midi
06322 Cannes La Bocca
France
33 92927391

Michael Farrington
Farrington Lockwood Company Ltd.
100 Terrance Matthews Cres.
Kanata, Ontario
CANADA K2M1P7
(613) 591-0754

David Feder
Electrochemical Energy
Storage Systems, Inc.
35 Ridgedale Ave.
Madison, NJ 07940
(201) 377-0163

Tony Felts
NWSC
Code 30523
Crane, IN 47522
(812) 854-1593

Nicanor Flordeliza
GE Americom
4 Research Way
Prineton, NJ 08540

Robert W. Francis
The Aerospace Corporation
MS/M4-988
2350 East El Segundo Blvd.
El Segundo, CA 90245-4691
(213) 336-6273

Allan Frandsen
NASA Headquarters
Code ES
Washington, DC 20546
(202) 453-1676

Kenneth Fuhr
Martin Marietta Astronautics
P.O. Box 179
Denver, CO 80201
(303) 977-4495

Chris Garner
Naval Research Laboratory
Code 8112
4555 Overlook Ave., S.W.
Washington, DC 20375
(202) 767-9075

Stephen J. Gaston
RCA
Astro Space Division
Princeton, NJ 08543-0800
MS 410-2-C19
(609) 426-2559

Pete George
NASA/MSFC
Bldg. 4487
Code EB 12
Huntsville, AL 35812

Richard Gerber
Aerospace
Box 92957
MS M6-213
Los Angeles, CA 90009
(213) 416-7033

Olga Gonzalez-Sanabria
NASA/LERC
21000 Brookpark Rd.
Mail Stop 309-1
Cleveland, OH 44135
(216) 433-5252
ODGONZALEZ

Lester Gordy
U.S. Army
8219 Running Creek Ct.
Springfield, VA 22153
(703) 695-3516

Jeffrey Gosciniak
Eveready Battery Co.
P.O. Box 45035
Westlake, OH 44145
(216) 835-7719

Jack Goualard
SAFT
156 Avenue de Metz
93230 Romainville
France
(33)-4843 9361

Joe C. Gowdey
NASA/LaRC
MS 433
Hampton, VA 23665
(804) 865-4621

Janet Grala
RCA
Astro Space Division
MS 410-2-C19
Princeton, NJ 08543-0800
(609) 426-3349

Robert S. Green
GTE Spacenet Corporation
1700 Old Meadow Rd.
McLean, VA 22102
(703) 848-0452

Arnold Hall
Whittaker-Yardney Power Systems
82 Mechanic St.
Pawcatuck, CT 02891
(203) 599-1100

Steve Hall
NWSC
Code 30523
Crane, IN 47522-5030
(812) 854-1593

Gerald Halpert
JPL
4800 Oak Grove Dr.
MS 277-212
Pasadena, CA 91109
(818) 354-5474

Zia Haq
Energetics
9210 Rt. 108
Columbia, MD 21045
992-4000

John Harvey
Marconi Space Systems Limited
Anchorage Rd.
Portsmouth, England
(0705) 664966

Gregg A. Herbert
JHU/APL
John Hopkins Rd.
Laurel, MD 20707
(301) 953-5000

Terry L. Hershey
Aerospace Corp.
P.O. Box 92957
Los Angeles, CA 90009
(213) 336-6273

Paul Howard
P.L. Howard Associates, Inc.
P.O. Box 280
Greensboro, MD 21639
(301) 482-6088

Daniel L. Hutchins
Western Development
Laboratories Division
3939 Fabian Way
Palo Alto, CA 94303
(415) 852-4715

Warren Hwang
Aerospace Corp.
Mail Stop M2-275
P.O. Box 92957
Los Angeles, CA 90009
(213) 336-6962

Ian Jenkins
MBB Space System Group
P.O. Box 801169
8000 Munich 80
WEST GERMANY
498963810253

Quentin Kampf
Freudenberg Nonwovens
221 Jackson Street
Lowell, MA 01852
(617) 454-0461

Vic Kardarpar
General Dynamics
Space System Division
P.O. Box 85990
MZ 24-8721
San Diego, CA 92138
(619) 547-4017

John Kelley
Exide Corporation
19 W. College Ave.
Yardley, PA 19067
(215) 493-7203

Heribert Kickel
Silberkraft Leichtakkumulatoren
Meidericher Str. 6-8
D-4100 Duisburg 1
0203-3002-182

Randolph C. Kientz
Gates Energy Products
P.O. Box 114
Gainesville, FL 32602
(904) 462-3557

David Kirkpatrick
Lockheed
Bldg. 551, Org. 62-12
1111 Lockheed Way
Sunnyvale, CA 94089
(408) 756-6149

Chip Koehler
Ford Aerospace & Comm. Corp.
MS Mail Station G-45
3939 Fabian Way
Mail Station G-45
Palo Alto, CA 94303
(415) 852-5133

Albert A. Koenig
Chloride Silent Power, Ltd.
940 W. Valley Rd.
Suite 1804
Wayne, PA 19087
(215) 341-9207

Paul W. Krehl
Electrochem Industries
10000 Wehrle Dr.
Clarence, NY 14031
(716) 759-2828

Paul Leigh
Fairchild Space Co. &
JHU/APL
20301 Century Boulevard
Germantown, MD 20874
(301) 953-5000 ext. 4034

Herman A. Lewis, Jr.
McDonnell Douglas Astronautics Co.
5301 Bolsa Ave.
Huntington Beach, CA 92647
(714) 896-3137

Stacy Lewis
GE American Communications
4 Research Way
Princeton, New Jersey 08540
(609) 987-4350

Hong Lim
Hughes Research Lab
MS RL70
3011 Malibu Canyon Rd.
Malibu, CA 90265

David Linden
Duracell
78 Lovett Ave.
Little Silver, NJ 07739
(201) 741-2271

Stephen M. Lipka
American Cyanamid Co.
P.O. Box 60
1937 West Main Street
Stamford, CT 06904
(203) 348-7331

Michael Mackowski
McDonnell Douglas
P.O. Box 516
St. Louis, MO 63166

Tyler X. Mahy
Central Intelligence Agency
c/o OTS
Washington, DC 20505
(703) 351-3912

Suzanne Maras
NASA/GSFC
Code 711.1
Greenbelt, MD. 20771
(301) 286-6279

Nehemiah Margalit
TRACOR Inc.
Tracor Battery Technology Center
3805 Mt. Vernon Ave.
Alexandria, VA 22305
(703) 769-6800

Steven P. Marquis
U.S. Patent Trademark Office
2021 Jefferson Davis Highway
Arlington, VA 22202
(703) 557-6680

J. Matsumoto
Aerospace Corporation
Mail Stop M2-275
P.O. Box 92957
Los Angeles, CA 90009
(213) 336-1526

Dean Maurer
AT&T Bell Labs
Room 1E 223
600 Mountain Ave.
Murray Hill, NJ 07974
(201) 582-3237

Richard H. Maurer
John Hopkins Applied Physics Lab
Johns Hopkins Rd.
Laurel, MD 20707
(301) 953-5000 Ext. 4009

Greg McDonald
MCI
P.O. Box 291
Clarksburg, MD 20871
(301) 540-5409

William McHugh
GTE
520 Winter Street
Waltham, MA 02254
(617) 466-3609

George Methlie
CIA
2120 Nathoa Ct.
Falls Church, VA.
(703) 533-1499

Vernon Milke
NASA/GSFC
Code 711
Greenbelt, MD 20771
(301) 286-8477

Gene J. Miller
JHU/APL
John Hopkins Rd.
Laurel, MD 20707
(301) 953-5000

Lee Miller
Eagle-Picher Industries, Inc.
P.O. Box 47
Joplin, MO 64802
(417) 623-8000

Tom Miller
NASA/LERC
Mail Stop 500-222
21000 Brookpark Rd.
Cleveland, OH 44135
(216) 433-6300

George Morrow
NASA/GSFC
Code 711
Greenbelt, MD 20771
(301) 286-6691

Kim Nagel
U.S. Army
SLAG - DAMO
Washington, DC 20004
(202) 695-3516

David Nawroeici
Lockheed
4935 Paseo Olivos
San Jose, CA 95130
(408) 743-7236
(408) 370-2847

Robert Nowak
Office of Naval Research
Code 113ES
800 N. Quincy St.
Arlington, VA 22217-5000
(202) 696-4409

Adriano M. Orsi
Fiar S.p.A.
Via Montefeltro, 8
20156 Milano
Italy
02-35790240

Charles Palandati
4915 56 Avenue
Hyattsville, MD 20781
(301) 277-8007

George B. Park
American Cyanamid Co.
P.O. Box 60
1937 W. Main Street
Stamford, CT 06904-0060
(203) 348-7331

Balan Pinchas
NASA/Goddard Space Flight Center
Code 743.3
Greenbelt, Maryland 20771
(301) 286-5681

Geoffrey Prentice
Department of Chemical Engineering
Johns Hopkins University
Baltimore, MD 21218
(301) 338-7006

Vince Puglisi
GATES
P.O. Box 114
Gainesville, FL 32602
(904) 462-4457

Guy Rampel
Gates Energy Products
P.O. Box 114
Gainesville, FL 32602
(904) 462-3521

Robert Richards
Martin Marietta Astronautics
P.O. Box 179
Denver, CO 80201
(303) 977-3828

Gilbert Roth
NASA Headquarters
Code Q-1
Washington, DC 20546
(202) 453-8971

Frank Scalici
INTELSAT
Mailbox 34
3400 International Dr., N.W.
Washington, D.C. 20008-3098
(202) 944-7353

Stephen F. Schiffer
GE/RCA Astro Space Division
MS 410-2-C19
P.O. Box 800
Princeton, NJ 08540

Norm Schulze
NASA Headquarters
Code QP
Washington, D.C. 20546
(301) 453-2742

Kenneth Schwer
McDonnell Douglas
P.O. Box 516
E454/107/2/CIO
St. Louis, MO 63166
(314) 233-2366

Eddie Seo
Gates Corp.
P.O. Box 5887
Denver, CO 80217
(303) 744-4614

Tamotsu Shirogami
Toshiba Corp.
Space Program Division
1, Komukai-Toshiba-cho,
Saiwai-Ku, Kawasaki 210
Japan
(044) 548-5253

Robert Siegler
Electrochem Industries
10,000 Wehrle Drive
Clarence, NY 14031
(716) 759-2828

D. Sieminski
Electrochem Industries
10,000 Wehrle Drive
Clarence, NY 14031
(716) 759-6901

Jack Sindorf
Johnson Controls, Inc.
P.O. Box 591
Milwaukee, WI 53201
(414) 961-6494

Nick Smilanich
Eveready Battery Co.
P.O. Box 45035
Westlake, OH 44145
(216) 835-7755

David Smith
Altus Corp.
1610 Crane St.
San Jose, CA 95112
(408) 436-1300

Marc A. Smith
GTE Spacenet Corporation
1700 Old Meadow Road
McLean, VA 22102
(703) 848-0414

John J. Smithrick
NASA LERC
21000 Brookpark Rd.
Cleveland, Ohio
(216)433-5255

Frank Snow
U.S. Navy - SPAWAR
Attn: PMW 142-52A
Washington, DC 20363-5100
(202) 692-7137

Thomas Spitzer
NASA/KSC
CS-EED-32
KSC, FL 32899
(FTS) 8-823-3690

Steven Stadnick
Hughes Aircraft Co.
P.O. Box 92919 Bldg. S41
MS/A-315
L.A. Airport Station
Los Angeles, CA 90009
(213) 648-9322

Robert Staniewicz
SAFT America
107 Beaver Court
Cockeysville, MD 21030
(301) 771-3200

Robert Stearns
GE Astro Space Division
P.O. Box 8555
Philadelphia, PA. 19101

Joseph Stockel
U.S. Govt.
5910 Granby Rd.
Derwood, MD 20855
(703) 351-2065

Martin Sulkes
USALABWM
SLCET-PB
Ft. Monmouth, NJ 07703-5000
(201) 544-2458

Ralph M. Sullivan
JHU/APL
John Hopkins Rd.
Laurel, MD 20707
(301) 953-5095

David Surd
Catalyst Research
3706 Crondall Lane
Owings Mills, MD 21117
(301) 356-2916

Larry Swette
Giner, Inc.
14 Spring St.
Waltham, MA 02254
(617) 899-7270

Larry Thaller
NASA/GSFC
MS 301-3
21000 Brookpark Rd.
Cleveland, OH 44135
(216) 433-6146

Helmut Thierfelder
G.E. Astro Space Division
P.O. Box 8555
Philadelphia, PA 19101
(215) 354-2027

Bill Thompson
NASA/GSFC
Code 711
Greenbelt, MD 20771
(301) 286-8014

Sid Tiller
NASA/GSFC
Code 711
Greenbelt, MD 20771
(301) 286-6489

Paul Timmerman
JPL
MS 277-108
4800 Oak Grove Dr.
Pasadena, CA 91109
(818) 354-5388

Hari Vaidyanathan
COMSAT Labs
22300 Comsat Dr.
Clarksburg, MD 20871
(301) 428-4507

James R.Waggoner
Catalyst Research
3706 Crondall Lane
Owings Mill, MD
(301) 356-2400

Harry Wannemacher
NASA/GSFC
Code 711
Greenbelt, MD 20771
(301) 286-5914

Harry Wajsgras
NASA/GSFC
Code 711
Greenbelt, MD 20771
(301) 286-6158

Don Webb
Martin-Marietta
P.O. Box 179
MS S-4017 Dept. 4345
Denver, CO 80201
(303) 977-3833

Steven P. Wicelinski
Catalyst Research
3706 Crondall Lane
Owings Mills, Maryland 21117
(301) 356-2914

Thomas H. Willis
AT&T-TS
50 Lawrence Road
Springfield, NJ 07081
(201) 467-7383

Richard Wissoker
GTE Government Systems
520 Winter St.
Waltham, MA 02154
(617) 466-3216

Cliff Wooten
Contel ASC
P.O. Box 370687
Decatur, GA 30037
(404) 244-2302

Koichi Yamawaki
National Space Development
Agency of Japan
Tsukuba Space Center
2-1-1, Sengen, Sakura-Mura,
Nihari-gun, Ibaraki-ken
305 Japan
(0298) 51-2271

Thomas Yi
NASA/GSFC
Code 711
Greenbelt, MD 20771
(301) 286-3051

Robert Youngblood
GE American Communications
Four Research Way
Princeton, N.J. 08540-6684
(609) 987-4121

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

FOURTH-CLASS MAIL
POSTAGE & FEES PAID
NASA
PERMIT No. G27

Code QW

Shahid Habib
NASA Headquarters
Code QE
Washington, DC 20546

NHQ FORM 159 J